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PREDICTION OF SLAGGING AND FOULING OF LIGNITE ASH

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EXECUTIVE SUMMARY

In this project the ash sintering test is being examined as a means of determining fouling tendencies of Saskatchewan lignites. Predictions from this test are compared to power plant experiences and empirical relationships based on ash composition.

For ashes that are produced by ASTM ashing conditions there is a reasonable correlation between ash compressive strength and ash fouling potential. However, these ashes have higher sulfate levels and more irregular morphology than do power plant ashes. This results in the laboratory ashes having higher compressive strengths at lower sintering temperature and greater tendencies to deform than corresponding fly ashes. Therefore, the data generated by these tests lead to subjective interpretations. Further work is suggested so that these effects can be reduced.

Ashes generated by low temperature radio frequency plasma ashing do not achieve compressive strengths that correspond well with their fouling behaviour. Difficulties are noted in obtaining uniformly low levels of residual organic material. In the course of this ashing procedure, conversion of iron containing minerals to ferric oxide is observed. Elevated levels of nitrates are also determined. In addition to these chemical difficulties, the great amount of time expended to secure sufficient ash for sintering tests appears to make this technique impractical.

Ashes produced by the CCRL combustion rig are similar to fly ashes and meaningful predictions of fouling activity from compressive strength appear possible. Also the sintering test appears useful in assessing the fouling potential of different kinds of ash produced by the same lignite. However, some of the combustion rig ashes contain elevated quantities of sulfate and some variation in particle size distribution is noted. Since the use of the CCRL combustion rig to routinely predict fouling phenomena is clearly impractical, effort should be expended in constructing a small-scale combustion rig that will produce spherical fly ash-like particles. The combustion conditions of the rig should be sufficiently flexible so that different amounts of volatile material such as SO_3 can be driven from the ash so that the chemical composition of the ash is similar to what is generated at power plants.

Tests on ASTM ashes with anti-fouling additives show an overall reduction in compressive strength with increasing additive. Since some of the changes in the magnitude of compressive strength are relatively small, the ratio of additive to ash used in these tests is much greater than what is required to alleviate power plant fouling. In performing future additive tests, a more reliable method of incorporating the additive into the ash matrix is desirable.

The empirical relationships that were examined gave correlations between predictions of ash fouling and actual fouling behaviour; however, they cannot be readily used in all cases. Both the ash-cone fusion test and the sintering test appear more useful in predicting ash fouling tendencies. If the ash sintering test is to be used more regularly

to predict ash fouling tendencies, development of a readily usable laboratory method that produces lignite ash that more closely resembles power plant ash is required. The greatest difficulties with laboratory produced ash appear to be its irregular morphology and high sulfate content. Construction of a bench scale combustion rig to generate simulated power plant ash deserves considerable work in future projects.

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1. OBJECTIVE AND INCENTIVES

The overall objective of this project was to investigate the slagging and fouling tendencies of Saskatchewan lignites in order to be able to better predict and understand these phenomena, and to help overcome problems associated with them.

Currently several experimental techniques and empirical formulae are available to predict fouling and slagging behaviour. These methods have been assessed for their applicability to Saskatchewan lignite and consideration has been taken of information useful in developing a sintering test of laboratory produced lignite ash.

The high ash content of Saskatchewan lignite has in the past led to slagging and fouling problems which interfere with generation of electricity. At the present time these problems are largely under control by using the limestone dosing technique, which was developed by the Saskatchewan Power Corporation. As the Corporation becomes forced to use remaining reserves of lower grade lignite, existing methods of treating fouling and slagging will not be adequate. Therefore, a greater understanding of the underlying principles of slagging and fouling is required so that an appropriate new means of combatting fouling and slagging may be developed.

Development of a reliable means of predicting slagging and fouling and a suitable method of alleviating them is necessary for production of power from coal at optimum efficiency. Development of a reliable control of

slagging and fouling will increase boiler availability, will make boiler cleaning and ash removal easier and will reduce boiler maintenance.

2. INTRODUCTION

2.1. Empirical Relationships Between Ash Composition and Slagging and Fouling

Ever since coal combustion has been used as a means of generating electricity, problems associated with the mineral matter of some coals have been noted. On hotter surfaces of the power plant system, molten ash or slag accumulations can occur. In cooler areas of the system, agglomerates of ash particles can accumulate, resulting in fouling. Both of these phenomena interfere with efficient heat transfer and prolonged plant closures may be necessary to alleviate problems resulting from excessive deposit levels.

Much work has been devoted to establishing a relationship between the elemental constitution of a coal ash and the tendency of inorganic coal material to cause slagging and fouling problems. However, the inorganic matter of coal consists of numerous elements arranged into a great number of compounds which have considerably different chemical and physical properties and which may undergo significant chemical and physical transformations during the process of combustion. Also, the elemental composition of coal mineral matter differs greatly among and sometimes within the various ranks of coal. Consequently, the success of establishing fouling and/or slagging correlations with the elemental composition of coal ash has been limited. General trends are difficult to establish and are sometimes contradictory as shown by a recent study which concluded that calcium was one of the least desirable constituents for

retarding ash fusion (Huffman et al., 1981), while Saskatchewan Power Corporation power plant experiences have shown addition of calcium to be very effective in reducing slagging and fouling (Anderson et al., 1977; Baker, 1981; and Baker and Gardiner, 1978).

Work to establish a relationship between ash softening and ash constitution began with European coals, and as early as 1897 Prost offered the following expression for a 'refractory quotient', Q, based on the study of twenty-three Belgian ashes (Watt, 1969):

$$Q = \frac{O \text{ in } Al_2O_3 \;/\; (O \text{ in } CaO + O \text{ in } Fe_2O_3 + O \text{ in } MgO)}{(O \text{ in } SiO_2) \;/\; (O \text{ in } Al_2O_3)} \qquad (1)$$

where the temperature of ash fusion generally increased with the parameter Q (O = weight of oxygen in the ash resulting from the metal oxide referred to).

In 1932 a relationship between ash softening temperature and the ratio:

$$R = \frac{(SiO_2 + Al_2O_3)}{(Fe_2O_3 + CaO + MgO + Na_2O + K_2O)} \qquad (2)$$

was suggested (Nicholls and Selvig, 1932).

Terms similar to those in Equation (2) occur in many expressions trying to relate ash fouling and slagging tendencies to ash composition. However, it was noted that even in the limited selection of coal ashes studied to derive this experimental relationship some ashes could deviate

substantially from their predicted behaviour.

Other investigators have attempted to assign relative strengths of effectiveness of the various components, resulting in expressions such as the following:

$$R_m = \frac{3.3\ SiO_2 + 1.96\ Al_2O_3}{2.5\ Fe_2O_3 + 3.57\ Ca + 5.0\ MgO + 3.22\ (Na_2O + K_2O)} \qquad (3)$$

(Majumdar et al., 1956-7)

or

$$R_s = \frac{SiO_2}{Al_2O_3} \times \frac{SiO_2 + Al_2O_3}{FeO + 0.6\ (CaO + MgO + Na_2O + K_2O)} \qquad (4)$$

(Barrett, 1945)

Other proposed ash softening-ash composition relationships include the following:

$$RB = \frac{SiO_2 + Al_2O_3 + MgO}{CaO + Fe_2O_3 + K_2O} \qquad (5)$$

(Beausigneur, 1963)

$$P = \frac{Fe + Mn_3O_4 + MgO + CaO}{SiO_2 + Al_2O_3} \qquad (6)$$

(Knaust, 1960)

$$R_a = \frac{SiO_2 + P_2O_5}{Al_2O_3 + Fe_2O_3 + CaO + MgO} \qquad (7)$$

(Novitskii et al., 1974)

and

$$R_b = \frac{Fe_2O_3 + FeO + MgO}{CaO + Na_2O + K_2O + CaF_2} \quad (8)$$

(Zhukova and Sheludyakov, 1978)

The above relationships were usually derived for a specific coal being studied and could not be applied to other types of coals. For example, Equation (6) contains a Mn_3O_4 term which is generally not considered to be of significance in most coals. Relationships including other components, such as TiO_2 and P_2O_5 have also been developed for several coal ashes where they are important. The relationships which have been developed have shown varying degrees of success. Equation (2), which was proposed in 1932, is used quite extensively as a major part of relationships describing a wide variety of coals. However, the more recent Equation (7) has been of little value, even for the coal ashes that were under investigation.

In developing ash composition-ash fusion relationships, the metallic elements present are generally considered as oxides. The nature of oxides present can vary depending on the nature of the atmosphere in contact with the ash. For example, Fe_3O_4 (decomposition point = 1538°C) is favored in oxidizing atmospheres while FeO (melting point = 1420°C) may form in reducing atmospheres. Reducing atmospheres enhance the formation of sub-oxides which in general are more volatile than conventional oxides found in oxidizing atmospheres. This property is reflected in generally lower ash fusion temperatures occurring in a reducing atmosphere compared with those in an oxidizing atmosphere.

Clearly relationships dependent on numerous elements are complex and difficult to represent pictorially. However, there is an obvious benefit

to representing ash fusion tendencies as simply as possible, and early workers attempted to describe ash fusion in ternary phase diagrams (Estep et al., 1934), an approach which is still being used (Huggins et al., 1981). An alternate treatment, which has been used for many years (Harrington, 1941), is to classify each metal oxide present in coal ash as basic or acidic, and then to predict slagging and fouling tendencies primarily on the relative amounts of acidic (usually SiO_2, Al_2O_3, TiO_2 and possibly P_2O_5) cr basic (usually CaO, MgO, Fe_2O_3, Na_2O and K_2O) components present. For example, a fouling factor (Winegartner, 1974):

$$R_f = \frac{\text{Base}}{\text{Acid}} \times \%\ Na_2O \text{ in coal ashed by ASTM methods} \qquad (9)$$

and a slagging factor (Winegartner, 1974):

$$R_s = \frac{\text{Base}}{\text{Acid}} \times \%\ S \text{ in dry coal} \qquad (10)$$

have been developed to predict these tendencies for a given coal. Such simple relationships appear to have some success for some coals, but difficulties arise when general application is attempted. Consequently, the basic components have been separated into dolomitic and non-dolomitic and the so-called dolomite ratio:

$$D.R. = \frac{(\%\ CaO + \%\ MgO)\ 100}{\%\ CaO + \%\ MgO + \%\ Fe_2O_3 + \%\ Na_2O + \%\ K_2O} \qquad (11)$$

(Duzy, 1967; Markley, 1967)

is now accepted as a useful parameter for predicting coal ash fusibility. Similarly, acidic components of ash have been refined so that the silica to alumina ratio is used to assess temperatures at which coal ash will flow

(Winegartner and Rhodes, 1975). From these considerations, graphical representations have been developed to indicate the temperature at which ash flow may be expected.

Monitoring certain acid-base constituents as a means of predicting ash fouling and slagging tendencies has been studied, and the ratio between the sum of the MgO and CaO content and the SiO_2 content has been proposed as a means of predicting ash softening (Lebedev et al., 1975).

While acid-base considerations are often used in assessing slagging and fouling tendencies, several workers have tried to establish relationships dependent on the specific constituents of coal ash. Boiler fouling ratings such as:

$$R_{BF} = 0.38\ Na_2O + 0.006\ SiO_2 - 0.008\ CaO + 0.062\ Ash + 0.0037 \quad (12)$$

(Sondreal et al., 1972)

or

$$R_{BF} = 0.38\ Na_2O + 0.017\ SiO_2 - 0.13\ CaO - 0.24\ Ash + 6.17 \quad (13)$$

(Sondreal et al., 1977)

have been derived for North Dakota lignites. Similar relationships have been derived to predict ash softening temperatures for bituminous coal ashes (Sondreal et al., 1978b):

$$S_T(^{o}F) = 1164 + 12.1\ SiO_2 + 18.8\ Al_2O_3 + 7.2\ Fe_2O_3 + 83\ TiO_2 + 2.0\ CaO - 11.6\ MgO - 13.7\ Na_2O - 22.3\ K_2O \quad (14)$$

and for lignite ashes:

$$S_T(^{o}F) = 2236 - 6.9\ SiO_2 + 0.1\ Al_2O_3 - 4.3\ Fe_2O_3 - 128\ TiO_2 + 3.5\ P_2O_5 + 8.5\ CaO + 14.9\ MgO - 8.7\ Na_2O + 80\ K_2O - 5.1\ SO_3 \quad (15)$$

These linear relationships often apply for just a select series of coal ashes and low correlation coefficients are often associated with them. Higher order regression plots of the form:

$$Y = K + a_1x_1 + b_1x_2 + c_1x_3 + d_1x_4 \ldots + a_2x_1^2\ b_2x_2^2 + c_2x_3^2 + d_2x_4^2 \ldots + a_3x_1x_2 + b_4x_1x_3 + c_4x_1x_4 + d_4x_2x_3 \ldots \quad (16)$$

where Y is the dependent variable, such as ash fusion temperature; k, a, b, c, d, etc., are constants; and x_1, x_2, x_3, etc., represent ash components, have also been developed and correspond better to experimental data (Sondreal and Ellman, 1975), but it is felt that this treatment is too complex to be useful (Bryers and Taylor, 1976).

Most of the component-ash fusibility relationships have been developed for higher grade coals which have ash contents high in silica and alumina compared to lignite ashes, and many of these relationships do not apply for lignite. For example, most relationships predict that addition of lime to an ash will lower the temperature at which ash fusion occurs; however, such

treatment actually raises the temperature of lignite ash fusion.

Many workers have noted that adding a component to coal ash lowers the softening temperature until a certain percentage is reached, and then that temperature rises with further increases of that component. Attempts have been made to relate these minima to the acid-base content of the ash, with the minimum ash softening temperature occurring when the ash is made up of 55% basic constituents (Winegartner and Rhodes, 1975). Consequently, when lime is added to acidic higher grade coal ashes, the ash softening temperature decreases, while the ash softening temperature increases when lime is added to basic lignite ash. However, such acid-base considerations do not always apply since an increase in basic low melting Na_2O content generally decreases the ash softening temperature, and addition of large amounts of silica failed to produce an increase in ash softening temperature in tests carried out with Saskatchewan lignite (Anderson et al., 1977).

A summary of the types of empirical relationships used to predict slagging and fouling is presented in Table 1.

2.2. Experimental Methods for Determining Slagging and Fouling

The foregoing discussion has shown that there are considerable problems in predicting ash fouling and slagging tendencies based on the composition of the ash. There is also some difficulty in developing accurate experimental tests that indicate the ash fouling and slagging tendencies of a particular ash. The most common method currently used is the so-called ash-cone fusion test where a trigonal ash pyramid of set dimensions is heated at a specified rate of temperature increase and the

Table 1. SUMMARY OF EMPIRICAL RELATIONSHIPS USED TO PREDICT SLAGGING AND FOULING

Relationship

$$Q = \frac{O \text{ in } Al_2O_3 \;/\; (O \text{ in } CaO + O \text{ in } Fe_2O_3 + O \text{ in } MgO)}{(O \text{ in } SiO_2) \;/\; (O \text{ in } Al_2O_3)} \qquad (I)$$

Comment

Developed very early. Not widely used now.

Relationship

$$R = \frac{(SiO_2 + Al_2O_3)}{(Fe_2O_3 + CaO + MgO + Na_2O + K_2O)} \qquad (II)$$

Comment

Developed early. Has limited use for lignite ashes because it treats all basic constituent with equal weight. Forms part of numerous contemporary relationships.

Relationship

$$R_m = \frac{3.3\ SiO_2 + 1.96\ Al_2O_3}{2.5\ Fe_2O_3 + 3.57\ Ca + 5.0\ MgO + 3.22\ (Na_2O + K_2O)} \qquad (III)$$

Comment

Similar to Relationship (2). Uses molar instead of weight ratios.

Relationship

$$R_s = \frac{SiO_2}{Al_2O_3} \times \frac{SiO_2 + Al_2O_3}{FeO + 0.6\ (CaO + MgO + Na_2O + K_2O)} \qquad (IV)$$

Comment

Modification of Relationship (II). Considers differences in acidic components.

Table 1. (Cont'd.) SUMMARY OF EMPIRICAL RELATIONSHIPS USED TO PREDICT SLAGGING AND FOULING

Relationship

$$RB = \frac{SiO_2 + Al_2O_3 + MgO}{CaO + Fe_2O_3 + K_2O} \quad (V)$$

Comment

Developed for French coals. Is not useful for lignites because it does not consider sodium content.

Relationship

$$P = \frac{Fe + Mn_3O_4 + MgO + CaO}{SiO_2 + Al_2O_3} \quad (VI)$$

Comment

Not developed and not useful for lignites.

Relationship

$$R_a = \frac{SiO_2 + P_2O_5}{Al_2O_3 + Fe_2O_3 + CaO + MgO} \quad (VII)$$

Comment

Developed for Russian lignites but has met with little success.

Relationship

$$R_b = \frac{Fe_2O_3 + FeO + MgO}{CaO + Na_2O + K_2O + CaF_2} \quad (VIII)$$

Comment

Developed for Russian lignites with high calcium and significant fluoride levels. Not useful for lignites in general.

Relationship

Fouling Factor. (IX)

Comment

Not recommended for lignite ash.

Table 1. (Cont'd.) SUMMARY OF EMPIRICAL RELATIONSHIPS USED TO PREDICT SLAGGING AND FOULING

Relationship

Slagging Factor. (X)

Comment

Not recommended for lignite ash.

Relationship

Dolomite Ratio. (XI)

Comment

Differentiates basic constituents. Useful for lignite ashes.

Relationship

Silica Ratio. (XII)

Comment

Differentiates acidic constituents. Effect least pronounced for lignite ashes.

Relationship

$R_{SL} = MgO + CaO/SiO_2$ (XIII)

Comment

Developed for lignite ashes with high CaO. Not generally useful for all lignites.

Relationship

Regression Analysis. (XIV)

(a) First Order.

(b) Higher Order.

Comment

(a) Can be used for lignite or bituminous ashes or both. Works best for the ashes used to derive the relationship.

(b) Fits data better than first order. Often very complex. Works best for the ashes used to derive the relationship.

Table 1. (Cont'd.) SUMMARY OF EMPIRICAL RELATIONSHIPS USED TO PREDICT SLAGGING AND FOULING

Relationship

Phase Diagrams. (XV)

Comment

Normally use only a few constituents present in ash. Oversimplifications occur.

temperatures of four specific deformations of the ash pyramid are noted.

Since coal ash is a multi-component system, significant amounts of fluid may be formed before any deformation in the cone is noted (Huggins et al., 1981; Lebedev et al., 1974b). Thus, temperatures at which cone deformations occur may be several hundred degrees higher than temperatures at which fouling occurs. Also, the phenomenon of slagging involves primarily fluid material and the transformations that occur in the ash-cone fusion test generally involve a mixture of solid and liquid components.

The ash-cone fusion test enjoys widespread acceptance because it was established early (Fieldner et al., 1918), its predictions are generally meaningful and because there is no reliable and convenient alternate method to predict slagging and fouling tendencies. However, the ash-cone fusion method is subjective and does not provide definitive data for assessing ash behavior during combustion and deposition (Lee et al., 1980). The ash does not deform homogeneously and lower viscosity components sometimes separate from the rest of the more refractory ash components (Wolfe, 1962). Also, the ash-fusion temperatures of some severely fouling coal ashes were found to be similar to those of a number of coal ashes that do not cause fouling (Barnhart and Williams, 1956), and there are reports of no correlation between ash slagging properties and fusion behaviour (Schneider, 1981).

Several modifications of the ash-cone fusion test, such as observing a cylinder or a cube instead of a pyramid, or monitoring different deformation points, have been studied. To prevent any reaction with support material, ash cones have been studied while suspended (Wolfe,

1962). By placing a weight on top of a test cylinder and recording the weight's position as a function of time, the deformations have been monitored automatically and good agreement with the standard test has been reported (Bunte and Baum, 1928; Reerink, 1933). Changes in deformation have also been followed photographically (Bro, 1932) and by dilatometry (Rousseau, 1948).

In contrast to studying changes in the form and shape of large ash specimens, the softening points of coal ashes have been monitored by direct observation of a small quantity of loose ash heated under a microscope (Fulweiler, 1918). This method was aided by the development of the high temperature electron microscope (Endell and Ardenne, 1943; Endell et al., 1943). Conflicting reports have been made on whether or not the microscopic observations can be related to deformation points of the ash fusion test. However, due to the heterogeneous nature of coal ash, there are obvious difficulties in assuring that the microscopic specimens are representative of the whole ash sample. Hot stage microscopy has been used to study boiler wall deposits to determine which constituents are in certain parts of the deposit (Fessler et al., 1980); it has also been used successfully to detect differences in ashes with different slagging tendencies although their ash fusion data are similar (Sanyal and Williamson, 1981).

A direct test for assessing slagging potential of a given coal ash is to measure the viscosity of a given ash over a set temperature range. It has been established for a long time that viscosity values vary by a factor of 100 for ashes at a given stage of deformation in the ash-fusion test

(Reid and Cohen, 1944). The temperature at which an ash has a viscosity of 250 poise is of interest since the ash is then sufficiently fluid that it can be tapped from the furnace walls, and empirical ash composition-ash flow curves are often presented in terms of temperature required for an ash to be at 250 poise (Hunt and Channing, 1980). Also, the temperature range over which the slag converts from a solid to a free flowing liquid should be considered when interpreting slag viscosity information. If the change occurs over a very small temperature range, then boiler slagging tends to be little or no problem since any slag exists as a free flowing melt; however, if there is a considerable temperature range at which the slag exists as a viscous, "sticky", non-flowing melt, then slagging problems tend to be considerable (Corey, 1964).

Although ash viscosity measurements tend to give very direct information about the slagging potential of a given sample, use of this technique is not wide-spread because the experimental procedure is usually difficult, time-consuming and expensive.

Studies of slagging potential have been carried out by noting the contact angle at which a slag droplet adheres to a particular surface (Abbott et al., 1981; Moza and Austin, 1980), the temperature at which adherence occurs (Moza and Austin, 1979; Moza et al., 1980), and the force required to shear it from that surface (Austin et al., 1980; Moza and Austin, 1982; Moza et al., 1980). However, chemical reactions that occur between the slag and the surface, possibly resulting in evolution of gases, make contact angle measurements difficult (Raask, 1966) and the interpretation of generated data uncertain.

The preceding tests involve the study of a fluid material or a material changing from a solid to a melt. When boiler tubes are fouled, solid matter is deposited. Therefore, developing a test that studies solid material may be desirable. For example, the changes in ash surface area upon heating have been studied (Lewandawky, 1962). The ash sintering test (Barnhart and Williams, 1956) has also been proposed in order to obtain a more direct insight on the fouling tendencies of coal, and it has gained some acceptance (Barnhart and Contieri, 1963; Winegartner, 1974). In the test, as originally developed, fly ash was ignited in air at 900°F and pressed into cylindrical pellets of 0.75 inches in height and 0.5 inches in diameter by applying a pressure of 150 psi; no binder was said to be necessary to form the pellets and indeed was advised against, lest subsequent results be adversely affected. The pellets were then heated to a desired temperature, typically 1500°F, over a period of 1 1/2 hours, held at that temperature for 15 hours and then cooled for 2 1/2 hours before removal from the furnace. The compressive strength of the sintered pellets was then determined. The average compressive strength of six samples was determined to a value with an error of + 20%, and carrying this test out at four different temperatures was deemed necessary to yield adequate information about the fouling potential of the ash.

The ash sintering test has been shown to yield very useful information for higher rank coals (Barnhart and Contieri, 1963; Barnhart and Williams, 1956), but much lower compressive strengths have been observed when studying lignites of corresponding fouling tendencies (Barnhart and Contieri, 1963; Moore and Ehrler, 1976). The sintering test has also been used to study shale and peat ash (Baryshev, 1981). Recently a new ash

sintering test has been developed for coal ash prepared in the laboratory (Gibb, 1981). When the ash was prepared at 500°C, a good agreement between compressive strength and fouling potential was found. However, when an ashing temperature of 800°C was used, problems were noted for Australian brown coals.

Although the developers of this test stated that fly ash pellets can be obtained without the use of a binder, other workers found that the use of a binder was necessary (Lebedev and Privalikhin, 1969). The sintering test has been used to study ash fouling tendencies as the ash reacted with water (Sharlovskaya et al., 1969), sulfuric acid (Petrov et al., 1976), carbon monoxide (Lebedev et al., 1974a), sulfur dioxide (Dering et al., 1972), and chlorine (Sharlovskaya and Konstantinova, 1974).

Because the original procedure for the ash sintering test required a suite of twenty-four pellets to test an individual ash sample, this test was generally considered too labour intensive and costly to be practical. The magnitude of the compressive strength of an ash pellet depends on numerous phenonema that occur in the process that are difficult to quantify and control, so many pellets are required to be tested to assure a reliable compressive strength. For example, during the process of sintering, the size of the pellet decreases and this shrinkage has been used to estimate ash fouling tendency (Barnhart and Williams, 1956; Raask, 1979). However, pellet shrinkage is often relatively small and thus difficult to quantify. During the heating that causes sintering, parts of the pellet may become more fluid and electrical conductance may increase. Measurement of electrical conductance of hot ash pellets has been suggested as a means to

monitor sintering (Raask, 1979), but this requires complex equipment, and is probably not suitable for wide-spread application.

2.3. Mechanisms of Slagging and Fouling

Establishing the mechanism(s) by which slagging and fouling occur has not been easy. This is largely due to the great number of possible components in coal ash, the different forms in which they may be present and the complex transformations that can occur during combustion.

Coal mineral matter is present either as discrete particles or as individual ions bound to organic exchange sites. Lignite, being a low rank coal, has a higher percentage of carboxylic acid ion exchange sites than do higher rank coals. These acids readily form salts with alkali and alkaline earth cations, and thus lignites usually have higher calcium and sodium contents than do higher grade coals. Discrete mineral matter includes pyrite, alumina, silica, and clay minerals such as kaolinite, illite, and montmorillonite. Discrete mineral matter can occur as particles sufficiently large that they can be readily physically separated from the rest of the coal, or can be so finely dispersed that physical separation is not practical.

During combustion volatile material is often driven from the ash particle. Thus, part of the mineral matter may be finely dispersed when entering the flue gases (Smith, 1980). The residual material may coalesce as combustion proceeds (Sarofim et al., 1977). Usually the furnace temperature is sufficient to fuse any aluminosilicate present, thus aiding

particle agglomeration and resulting in particles that tend to be spherical in order to minimize surface tension. Once an ash sphere is formed, organic material trapped within can generate CO_2 and cause hollow cenospheres to be formed.

Larger extraneous coal ash particles will melt upon exposure to heat, and depending on their mass, may be carried along with the flue gases and be included as fly ash or may fall to the bottom of the furnace to become bottom ash.

Individual ash particles being carried by the flue gas stream may collide and further agglomerate (Ulrich, 1979), especially if fluid components are present (Elbirli et al., 1980). Further, the heat present in the flue gases will tend to drive off more volatile components of the ash particles which can then recondense on the particle surfaces when cooler regions are encountered. High temperatures will tend to decompose metal sulfates and carbonates to oxides and to aid conversion of metal sulfides to oxides. Consequently, treatment of mineral matter as largely oxides when considering fouling and slagging tendencies is justified to a certain extent, although SO_x in the flue gas stream may react with those oxides at lower temperatures to yield sulfates.

Volatilized mineral matter in the flue gases may condense on ash particles in the stream. In this way, inherent sodium can act as a flux to help bind solid ash particles together. The inherent mineral matter remaining in the stream may also condense on boiler tubes in various parts of the furnace and thus initiate fouling problems.

The build-up of ash deposits on boiler tubes can occur by a variety of pathways depending on the nature of the coal ash and the conditions of combustion used. However, fouling generally proceeds by an initial deposition of low melting ash components which then react with components in the flue stream so that the deposit is strengthened. As the deposit builds up, the outer layer becomes hotter and higher melting ash components can then become incorporated into the material (Sondreal et al., 1978a).

Coal ashes with high iron contents are noted for fouling and slagging problems. At temperatures below the initial deformation point in the ash-cone fusion test, free flowing fractions rich in iron are noted (Lebedev et al., 1974c). Iron in coal ash can be present in several forms, which will cause it to affect the fouling and slagging tendencies of the ash in different ways, depending on the nature of the iron. When iron is reduced from an oxide to metallic, a reduction in slag fluidity is noted, (Kapelson et al., 1972). If iron is present as a mixture of Fe and FeO fouling accumulations are noted, but if all the iron is oxidized to Fe_2O_3, then a decrease in deposit formation is noted (Kozlov and Rozkhov, 1977). A reduction in deposit strength upon magnetic separation has been noted (Bibby et al., 1978; Veretevskaya and Valdre, 1976).

Selective deposition of pyrite on furnace walls sometimes initiates ash deposit formation (Bryers, 1979), and initial ash deposit layers have been reported to contain up to 85% iron expressed as Fe_2O_3 (Marshak et al., 1981). Once pyrite is deposited on a boiler wall, it can then undergo reactions with the flue stream. As a result of exposure to water vapor some of the pyrite can be converted to FeO (Dik et al., 1977), and the

formation of a low melting eutectic of the two iron species can then initiate the fouling process (Dik et al., 1974a; Lebedev et al., 1974a). By using more efficient combustion which completely oxidizes this eutectic, fouling can be decreased (Karyakin, 1976). If an ash high in iron also has a high sulfur content, then reactions between the two components can enhance clinkering (Durmanov, 1981); and a eutectic of FeO and FeS can initiate fouling (Alekhonovich et al., 1982).

Calcium is another component that has been associated with slagging and fouling tendencies, with the presence of free CaO being widely associated with increased fouling. Ash consisting of more than 35% CaO has been reported as severely fouling (Pronin et al., 1982). Reduction in rates of deposit accumulations as combustion temperatures increase is attributed to conversion of free CaO to other calcium compounds (Bezdenezhnykh et al., 1970; Sharlovskaya, 1970). In high calcium ashes there is enhanced formation of $CaSO_4$ at high temperatures; in lower calcium ashes the calcium is incorporated into the ash alumino-silicate matrix (Dik, et al., 1974b). The formation of an initial ash deposit has been noted and fouling was propogated by subsequent cementitious reactions with other ash constituents (Komarova, et al., 1974); especially strong deposits are reported when similar amounts of CaO and SiO_2 are present (Marshak et al., 1981). Hardening reactions between CaO and water may also be significant (Logvinenko et al., 1971). CaO can also react with SO_2 in the flue gases. Of a series of ashes studied (Lebedev et al., 1974b), samples highest in free CaO achieved the greatest gain in weight and increase in strength upon exposure to SO_2. Reactions between CaO and SO_2 have also been noted in layers of ash built up after the formation of

initial iron-rich depositions (Georgiev and Tonchev, 1974).

Sulfation may be an important possible ash fouling reaction as substantial hardening of boiler tube deposits is noted when they are exposed to sulfuric acid below its dew point (Petrov et al., 1976).

Whether the atmosphere is reducing or oxidizing in nature may determine how extensive fouling may be. The presence of an oxidizing atmosphere has previously been shown to alleviate fouling by breaking up reduced iron eutectics that can form in reducing atmospheres. Other elements present may also be reduced from their conventional oxide in a reducing atmosphere. For example, the enhanced formation of SiO in the presence of CO and H_2O has been attributed to observed accelerations in fouling (Pugach et al., 1974). In an attempt to decrease formation of NO_x from combustion of North Dakota lignite, a reduction of excess air was attempted. NO_x formation was lowered slightly, but fouling was greatly enhanced (Honea et al., 1978).

The fouling potential of a fly ash is dependent on the size of its particles. Ash-cones made up of smaller particles deform at lower temperatures (Pugach et al., 1974; Karyakin, 1976). Smaller fly ash particles are also seen to exhibit higher compressive strength upon sintering (Dering et al., 1972) and harder deposits have been observed with smaller fly ash particles (Veretevskaya and Valdre, 1976).

The presence of sodium and potassium is generally associated with enhanced fouling and slagging phenomena. Compounds of these metals tend to

be low-melting and they are able to serve as a flux for the higher melting ash constituents. Ash fouling is especially marked if the alkali metal is present as a chloride (Watt, 1969; Sharlovskaya and Konstantinova, 1974) or as a sulfate (Tufte and Beckering, 1975). Once sodium is deposited on the boiler tube reactions may take place to further ehnance fouling. Thermodynamic considerations support the formation of sodium silicate species under power plant conditions (Wibberly and Wall, 1982a). The presence of supercooled sodium silicate compounds on the surface of ash particles has been suggested as a means of aiding particle agglomeration (Bocw, 1972); also reactions between soluble alkali compounds and silica have been reported to enhance deposit formation (Savic et al., 1976). Recent experimental evidence corroborates the formation of sodium silicate compounds under power plant conditions (Wibberly and Wall, 1982b).

Once alkali metals are deposited on boiler tubes, the deposit may heat up and eventually drive off the volatile alkali metals. The fouling of German lignite cakes is aggravated by increased amounts of sodium, potassium, sulfur and silicon (Hein, 1979a). However, in high temperature deposits, the sodium, potassium and sulfur levels decrease; the silicon remains, ensuring a tightly bound deposit (Hein, 1979b).

Deposits of North Dakota lignite ash that result from severe boiler tube fouling exhibit a white layer occurring along the length of the tube (Tufte and Beckering, 1975). This layer is enriched in Na_2SO_4, which presumably originates from inherent sodium that has reacted with SO_x. Inherent calcium may also react with SO_x, resulting in $CaSO_4$ depositing with the Na_2SO_4. If the calcium content of this layer is sufficiently

high, then fouling tends not to be such a severe problem; a three-fold excess of calcium over sodium has been suggested as adequate to prevent fouling phenomena (Baker, 1981). The inner layer enriched in Na_2SO_4 probably provides a sufficiently sticky surface to which ash particles can adhere, since they do not appear to readily adhere to naked metal (Austin et al., 1980). Ash adhesion may also be enhanced by the formation of some sodium silicates.

Once the initial Na_2SO_4 enriched layer is formed, ash particles can impact onto the boiler tube. The first particles that do stick to the inner layer are reasonably weakly bound and are held together by surface forces, retaining most of their structural integrity. Once the ash particles accumulate on a boiler tube, heat transfer is impeded and the outer surface of the deposit can heat up so that some of the particles can fuse. Once this happens an outer layer of strongly bound ash can build up as available fluxing material forms a melt and enhances the binding of the ash particles. Here again the presence of sodium is thought to be important as Na_2SO_4 (mp 884°C) can condense on the ash deposits in a fluid state and help bind the particles together so that a semi-continuous melt matrix is formed. Again the deposition of $CaSO_4$ (mp 1450°C) can counteract the fluxing tendency of Na_2SO_4 and fouling problems may not occur with lignite ashes high in calcium. Indeed the addition of calcium has been used with considerable success at SPC's Boundary Dam installation to combat fouling (Anderson et al., 1977; Baker, 1981).

2.4. Practices for Alleviating Slagging and Fouling

Although higher calcium contents in some higher grade coal ashes are associated with greater fouling and calcium is often added to increase slag fluidity so that it can be tapped more easily, the Saskatchewan Power Corporation (SPC) has had great success in combatting fouling by adding calcium. SPC adds calcium carbonate ($CaCO_3$) once every two hours to power station units to prevent fouling. If there are little or no deposits present, the $CaSO_4$ which forms in the flue gases can condense on the boiler tubes and prevent an accumulation of ash. If a deposit is already present, then calcium addition has been shown to weaken the deposit.

The total calcium addition constitutes only a small part of the amount of calcium present in the ash, so the possibility of the added calcium significantly affecting the bulk properties of the ash are slim. Diffusion of calcium along the surfaces of the ash particles would be a more plausible mechanism and thus penetration of calcium into the bonding matrix of an ash deposit could counteract the fluxing effect of any sodium present and weaken the deposit.

Attempts to alleviate fouling by adding MgO were effective but the quantities required rendered the process uneconomic (Michel and Wilkonson, 1955). Recently, success has been reported by using smaller quantities of MgO in a finely dispersed state (Radway and Boyce, 1977). MgO is thought to act as a scavenger of SO_3, thus alleviating SO_x emissions as well (Radway, 1978). Additives including both MgO and Al_2O_3 have also been used to control fouling (Dixit, 1978) and this type of additive has been used in

conjunction with first row transition metals which catalyze coal combustion (Anon, 1978). Organic additives have also been used to alleviate fouling (Vlacic, 1979). However, the use of additives to alleviate utility fouling problems is currently limited (Locklin et al., 1980).

Treatment of slagging often occurs by adding a fluxing agent so that the slag will drain more easily. Conventional fluxes include compounds of calcium, magnesium, silicon and sometimes alkali metals. Addition of the boron containing ore, colemanite, sodium borate, or organic boron derivatives has exhibited enhanced fluxing behaviour (Bennett and Kukin, 1977, 1979).

Sometimes additions that weaken slag can be made. Copper oxychloride has been shown to enhance the rate of slag crystallization (Kiss et al., 1972). The ash slag is then more readily broken up and disposed of. Similar observations have been noted when vermiculite is added to a coal stream (Engstrom and Bain, 1982). Additions of calcium have also weakened SPC slag deposits (Baker, 1981).

3. EXPERIMENTAL METHODS

Nine samples of Saskatchewan lignite ashes were studied for this project. Two came from the Poplar River Mine (PRML-1, PRML-2), two from the Boundary Dam Mine (BDML-1, BDML-2) one each from the Bienfait and Utility Mines (BML, UML) and three were taken from the Klimax Mine (KML-1, KML-2, KML-3).

Preparation of the lignites for the sintering test was started by air-drying portions of the parent lignites for 72 h and then passing them through a 60-mesh sieve. Ashes were prepared according to ASTM Method D 3174; however, in addition to obtaining ashes by heating at the prescribed 750°C, ashes from each lignite sample were produced by heating at 500°C. A 1.5 g sample of the ash made in this way was placed in a 1.3 cm die and treated with 70 MPa pressure. After the resulting pellet was taken to a desired sintering temperature in the 850-1050°C range over a period of 2 h, it was sintered at that temperature for 15 h. Once the pellet had been cooled to ambient temperature over a period of 2 h, it could then be tested for compressive strength.

All of the Saskatchewan lignites studied were also ashed by radio-frequency plasma. In order to ensure that a maximum of the lignite surface was exposed to the plasma, the lignite was ground so that it would pass through a 325-mesh sieve. Sieving was aided by the dispersion of the lignite in n-heptane. After being dried at 130°C for 15 h, the lignite was again dispersed in n-heptane and spread into a uniform translucent layer on quartz plates. Once the n-heptane had evaporated, the lignite was placed

in a Tegal Corporation Plasmod Low Temperature Plasma Asher and ashed at full r-f power for 24 h. Numerous repetitions of this procedure were required before sufficient ash was prepared to make pellets in the manner already discussed, and experiments could only be performed at one sintering temperature (1000°C).

Samples of slag, furnace wall ash and superheater ash were obtained from the Canadian Combustion Research Laboratory (CCRL) combustion rig. A variety of ashes derived from a Bienfait lignite was studied. As well as being produced from the unaltered parent lignite (BF-0), some of the Bienfait lignite ashes had resulted after the parent lignite had been treated with slug dosages of limestone to result in CaO additions constituting 0.15 (BF-1), 0.5 (BF-2), and 1.5% (BF-3) by weight of the lignite. Also, a continuous limestone feed was used to produce a lignite with an addition of 8% by weight (BF-4). In addition, one ash each was derived from present Onakawana (ONAK) and Klimax (KLIM) lignites. These ashes were passed through a 100-mesh sieve, and 2.0 g portions were mixed with 0.1 to 0.15 g of a 5% by weight paraffin wax in toluene binder, formed into pellets, compressed to 70 MPa and sintered under conditions similar to those for the laboratory-produced ashes.

A set of three or four pellets was usually used for each compressive strength determination so that reproducibility could be assured. Measurement of compressive strength was performed with a Labquip Corp. Cal-Tester that had been fitted with fibre pads on the ram and the base so that uniform loading could be assured and that effects of pellet surface imperfections could be minimized.

Determination of major element (SiO_2, Al_2O_3, Fe_2O_3, TiO_2, P_2O_5, CaO, MgO, SO_3, Na_2O, and K_2O) concentrations in the lignite ash was carried out by SPC, using ASTM Method D2795 with an additional 15 minute digestion with $HClO_4$, or by CanTest Ltd. using inductively coupled plasma spectroscopy (ICP). Data on equivalent samples obtained from the two different laboratories agreed within ASTM limits of variation. SPC spectrophotometric determinations were made with a Perkin Elmer Atomic Absorption Spectrophotometer, Model 360 or with a Perkin Elmer Double Beam UV-VIS Spectrophotometer, Model 124.

Proximate analyses of the lignite samples were made with a Fisher Coal Analyzer, Model 490. Lignite and lignite ash samples were analyzed for carbon, hydrogen and nitrogen using a Perkin Elmer Elemental Analyzer, Model 240B. Ash-cone fusion experiments were carried out with a natural gas Barrett Fusion Furnace, Model E.

Mineralogical analyses were performed by UMEX Inc. using both optical and X-ray diffraction techniques. Fine fraction particle size distribution determinations were made by the Ontario Research Foundation using a Quantimet 720 Image Analyzing Computer. Coarse fraction particle size measurements were carried out in-house using sieves.

4. COMPRESSIVE STRENGTH OF LABORATORY PRODUCED LIGNITE ASHES

4.1. Compressive Strength of Lignite Ashes Produced by ASTM Ashing Techniques

4.1.1. General

Following ultimate and proximate analyses performed on the parent lignite (Table 2), major and minor elemental analyses performed on the nine Saskatchewan lignite ashes produced at 500°C indicated that CaO contents varied from 12.1 to 18.5% and that the SO_3 content ranged from 6.3 to 20.9% (Table 3). The molar ratio between CaO and SO_3 was lowest for KML-3 (0.83) and highest for BDML-1 (3.40). The chemical composition of these ashes varied little from those produced at 750°C except in the case of KML-3 which had evolved sufficient SO_3 to raise the molar CaO:SO_3 ratio to 1.18. Mineralogical analyses performed on the ashes are shown in Table 4.

The ash morphology of the laboratory-produced ash is more irregular than power plant ashes with less surface enhancement of volatile components (Smith and Szladow, 1982). Over 90% of the ash passed a 200-mesh sieve and over 75% of the ash passed a 325-mesh sieve. In BDML-1, 90% of the particles are less than 9.0 u in diameter. As the ashing temperature is raised from 500 to 750°C, little change is noted in ash morphology or ash particle size distribution (Figure 1).

Table 2. PROXIMATE AND ULTIMATE ANALYSES OF SASKATCHEWAN LIGNITES

LIGNITE	% WATER	% VOLATILES	% ASH	% FIXED CARBON	% C	% N	% H
PRML-1	16.32	36.15	23.40	40.45	64.76	0.89	3.95
PRML-2	31.99	40.47	16.56	42.98	56.80	0.77	3.72
BDML-1	32.21	40.84	17.40	46.07	60.89	1.03	3.85
BDML-2	33.90	39.82	13.30	46.93	61.11	1.16	3.79
BML	29.10	41.86	13.05	45.10	61.01	1.01	3.83
UML	33.65	42.44	12.42	45.14	61.15	1.09	3.57
KML-1	33.85	42.75	12.85	45.67	61.17	1.08	3.67
KML-2	34.85	39.58	13.17	47.26	61.06	1.13	3.74
KML-3	34.25	41.01	11.84	46.20	61.11	1.11	3.65

Table 3. CHEMICAL COMPOSITION OF SASKATCHEWAN LIGNITE ASHES

COMPONENT / ASH TYPE	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O	[CaO]/[SO_3]
PRML-1	36.4	21.3	4.9	0.87	0.59	14.5	3.8	6.4	1.7	1.4	3.24
PRML-2	26.6	18.8	5.1	0.40	0.56	18.4	5.3	14.5	1.8	0.6	1.81
BDML-1	41.7	21.0	3.2	0.78	0.35	15.0	2.8	6.3	6.6	1.0	3.40
BDML-2	36.2	10.3	3.7	0.16	0.47	15.6	3.8	15.3	5.6	1.4	1.46
BML	32.5	23.9	4.5	0.38	0.67	13.1	2.9	10.4	7.2	0.2	2.60
UML	33.8	18.1	3.9	0.58	0.54	18.5	4.8	7.4	5.1	0.4	3.57
KML-1	43.3	19.0	3.9	0.64	0.72	12.1	2.6	7.2	4.2	0.6	2.40
KML-2	23.7	17.2	8.1	0.42	0.68	16.8	3.9	19.8	7.6	0.2	1.21
KML-3	25.6	16.1	13.6	0.47	0.71	12.1	2.6	20.9	5.9	0.2	0.83

Values listed are in percent by weight.

Table 4. MINERALOGICAL COMPOSITION OF SASKATCHEWAN LIGNITE ASHES

MINERAL / ASH TYPE	AMORPHOUS	QUARTZ	K-FELDSPAR	CALCITE	ANHYDRITE	BIOTITE	OPAQUE
PRML-1	60%	10%	20%	TRACE	MODERATE	TRACE	3%
PRML-2	80-85%	9%	MINOR	MINOR	MINOR	---	--
BDML-1	70-75%	19%	---	MODERATE	MINOR	---	--
BDML-2	75-80%	20%	V. MINOR	V. MINOR	MODERATE	TRACE	TRACE
BML	80-85%	16%	TRACE	MINOR	---	---	--
UML	75-80%	17%	MINOR	MINOR	MODERATE	---	--
KML-1	60-65%	35-40%	---	---	TRACE	---	--
KML-2	65-70%	15%	---	---	MODERATE	---	--
KML-3*	80%	13%	MINOR	---	MODERATE	---	6%

* ANALYZES FOR 1% IRON OXIDE

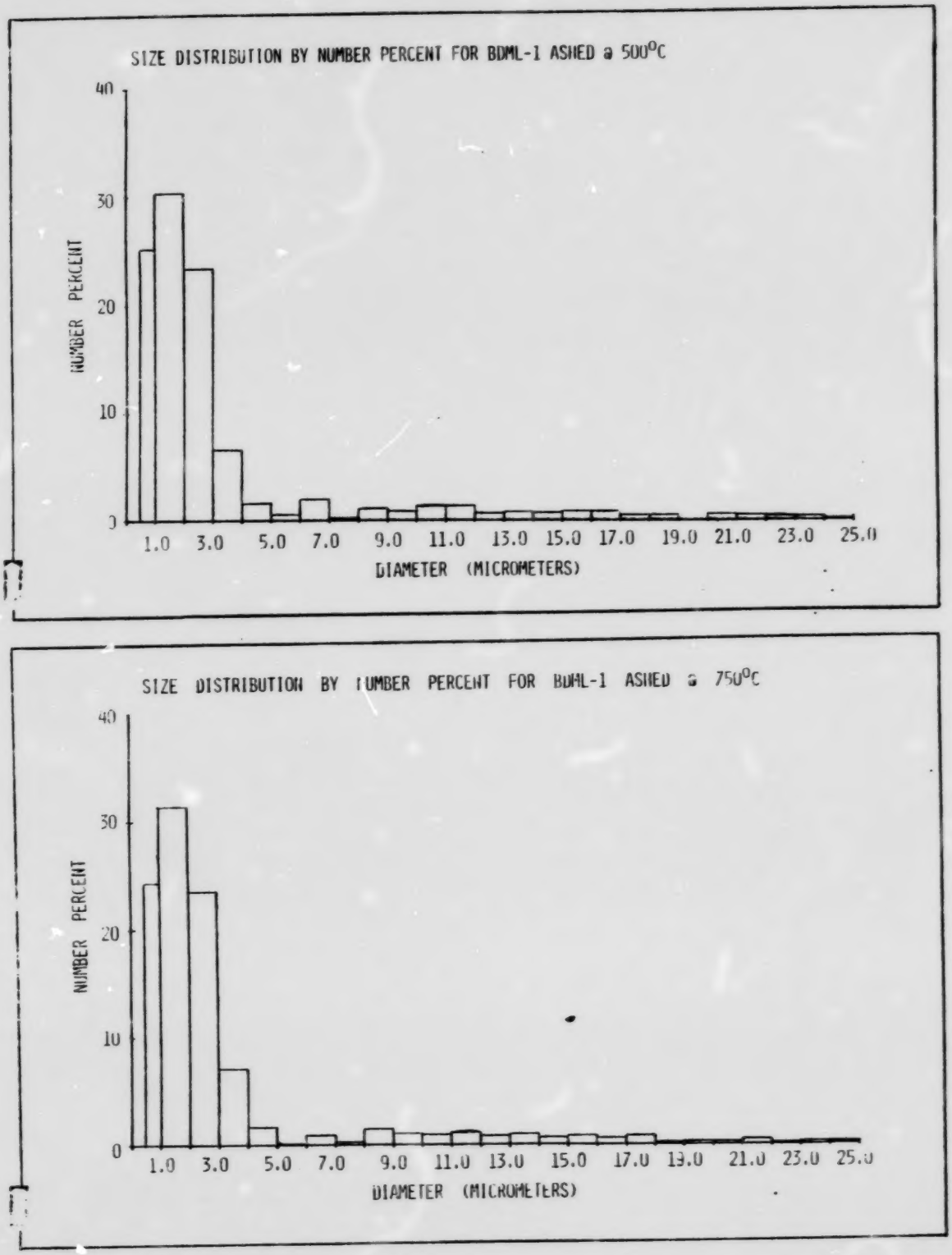


Figure 1. FINE PARTICLE SIZE DISTRIBUTION OF BDML-1 LABORATORY ASHES

4.1.2. Ashes Produced at 500°C

When the sintering test was first being developed, an ashing temperature of 500°C was used because this corresponded well with the 950°F (510°C) temperature that was used to treat fly ash samples in the established test (Barnhart and Williams, 1956). Reproducible results were readily obtained under these conditions and the compressive strengths of some lignite ashes initially studied corresponded well with their expected fouling behaviour (Smith and Szladow, 1982). Therefore, compressive strength tests were performed on the nine Saskatchewan lignite ashes that had been produced at 500°C.

In the early stages of examining the SPC sintering test, compressive strengths of ash pellets sintered at 1050°C were indicative of the ash fouling behaviour of the parent lignites. However, compressive strengths of some ashes have been reported to pass through a maximum as temperature is increased. Therefore, compressive strengths of the Saskatchewan lignite were measured over a sintering temperature range from 850-1050°C and a variety in behaviour patterns was noted (Figure 2).

Generally an increase in compressive strength with sintering temperature was observed; this is consistent with more sintering of ash particles occurring at higher temperature. However, some of the largest values of compressive strength occurred at lower end of the sintering temperature range. This behaviour contrasts markedly with what is observed in Saskatchewan fly ashes (Smith and Szladow, 1982) and the CCRL combustion rig ashes (Chapter 6), where compressive strengths are always lowest at the

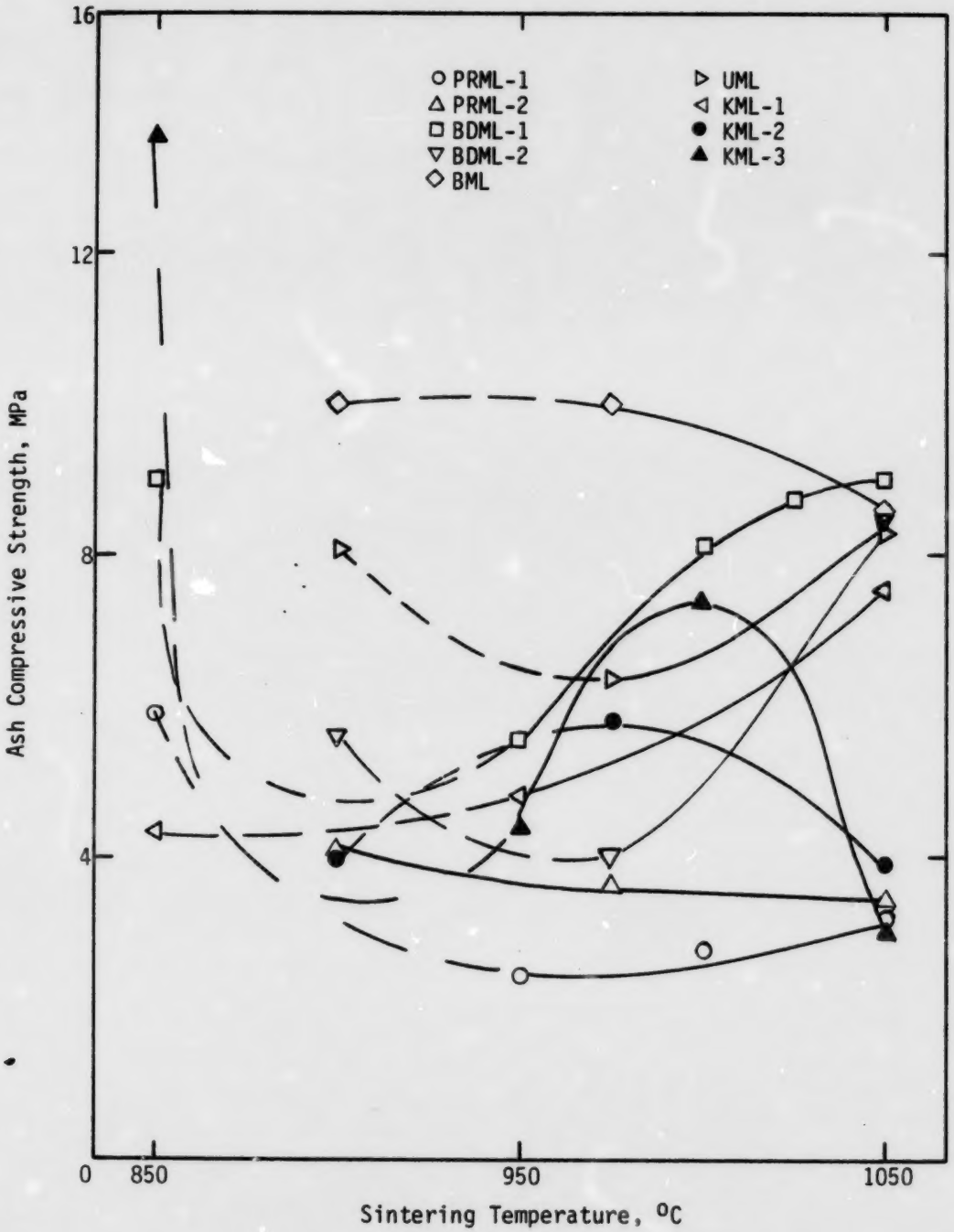


Figure 2. COMPRESSIVE STRENGTH OF SASKATCHEWAN LIGNITE ASH PREPARED AT 500°C AS A FUNCTION OF SINTERING TEMPERATURE

lowest sintering temperature.

This phenomenon could be related to the irregular morphology of the laboratory-produced ash particles which would allow for individual particles to interlock. The pressure used to produce the ash pellets could cause particle interlocking to occur and result in elevated compressive strength. This is supported by the observation that before sintering the laboratory-produced ash pellets are stronger than fly ash or CCRL ash pellets and that the ultimate compressive strength of the laboratory ash pellets increases linearly with pellet producing pressure (Smith and Szladow, 1982).

At a sintering temperature of 950°C, relaxation of the ash matrix could occur, and this would result in a lowering of compressive strength. Normal increases in compressive strength with sintering temperature could then take place.

The greatest magnitude of compressive strength of the laboratory-produced ashes is somewhat lower than the largest magnitudes noted for pellets resulting from fly ashes or CCRL combustion ashes. In the production of the latter ashes, volatile components such as sodium can be vapourized in the hotter portions of the fireball and then condensed on the surface of the ash particle in cooler zones. This allows surface enrichment of volatile components of fly ashes that does not occur in the laboratory-produced ashes. The surface of the fly ash particle would thus be rendered more fusible and increases in compressive strength due to enhanced sintering can occur for the fly ashes.

Although most of the laboratory ashes increased in compressive strength as higher sintering temperatures were used, at least two ashes (KML-2 and KML-3) were seen to pass through a compressive strength maximum. After pellets from these ashes were sintered at a temperature of 1050°C, their structure appeared porous. This could be due to volatilization of SO_3, since ashes from KML-2 and KML-3 are both very high in SO_3. The reduction of SO_3 could thus result in pellet weakening. In addition, these ashes were fairly high in Na_2O and pellet deformation resulting from the fusion of Na_2O-rich components could also cause decreased compressive strengths at elevated temperatures. The compressive strength of BML was lower at 1050°C than at other temperatures. This could be due to pellet relaxation not occurring until higher temperatures. Also, the sodium level of BML was exceeded only by that of KML-2 and this high concentration could result in pellet deformation at higher temperatures.

The laboratory ashes that had the lowest compressive strength were PRML-1 and PRML-2. These ashes originate from the Willowbunch lignite deposit, contain the lowest levels of sodium and are associated with almost no fouling problems. There is considerable cross-over among the compressive strength vs. sintering temperature curves of the remaining ashes. However, once pellet deformation due to high levels of volatile constituents associated with increased fouling potential and strength imparted due to pellet formation are taken into consideration, the following order of fouling potential can be proposed:

Most strongly fouling: KML-3, BML, BDML-1; Moderately to strongly fouling: KML-2, BDML-2, UML, KML-1; Weakly to non-fouling PRML-2, PRML-1.

The ash-cone fusion behaviour of these ashes was studied (Table 5).

Predictions of ash fouling order based on the elemental composition of the ash were also generated (Table 6). Individual constituents associated with increased fouling potential of lignite ashes are Na_2O, SiO_2 and SO_3. The constituent associated most with decreased fouling potential of lignite ashes is calcium. In addition to fouling potential orders considering the four above individual components, predictions based on a combination of the base-acid ratio and the dolomite ratio (Duzy, 1967), the fouling factor (Winegartner, 1974), a first order regression analysis* and a second order regression analysis** are reported.

Both experimental techniques indicate that the two Willowbunch lignite ashes are the least likely to cause fouling problems and the power plant behaviour of these ashes is consistent with this assessment. Predictions from the dolomite ratio and the first order regression analysis indicate the Willowbunch ashes are relatively non-fouling. However, except for the simplistic fouling factor (which is not even recommended for lignite ashes) and the sodium content, none of the empirical relationships indicate that these ashes are less fouling than all the others. Consequently, it appears that the development of an appropriate experimental test for fouling potential would be more useful than predictions based on ash composition.

*$S_T(^oF)$ = 2236-6.9 SiO_2 + 0.1 Al_2O_3 - 4.3 Fe_2O_3 -128 TiO_2 + 3.5 P_2O_5 + 8.5 CaO + 14.9 MgO - 8.7 Na_2O + 80 K_2O - 5.1 SO_3)
(Sondreal et al., 1977)

**$S_T(^oF)$ = 1027 - 3.725 SiO_2 + 39.067 Fe_2O_3 + 93.634 CaO + 0.8155 Al_2O_3 X SiO_2 - 0.2214 SiO_2 X CaO - 0.0975 SiO_2 X Na_2O - 0.488 SiO_2 X SO_3 - 0.8674 Al_2O_3 X CaO - 2.4234 Fe_2O_3 X CaO + 2.077 Fe_2O_3 X MgO - 0.8765 CaO^2 - 1.3431 Al_2O_3 X SO_3 + 0.0764 SO_3^2)
(Sondreal and Ellman, 1975)

Table 5. ASH-CONE FUSION DATA FOR SASKATCHEWAN LIGNITE ASHES

FUSION POINT / ASH TYPE	REDUCING ATMOSPHERE				OXIDIZING ATMOSPHERE			
	IDP	HP	SP	FP	IDP	HP	SP	FP
PRML-1	1115	1180	1190	1245	1165	1220	1245	1295
PRML-2	1110	1125	1155	1180	1150	1165	1170	1250
BDML-1	1060	1100	1130	1215	1080	1130	1145	1240
BDML-2	1035	1140	1160	1175	1065	1150	1210	1240
BML	1050	1105	1115	1175	1090	1125	1170	1340
UML	1030	1090	1095	1150	1070	1140	1165	1290
KML-1	1080	1140	1160	1215	1105	1170	1205	1285
KML-2	1030	1070	1100	1150	1090	1160	1195	1295
KML-3	1010	1045	1065	1105	1085	1265	1280	1325

Values listed in ^{o}C.

Table 6. PREDICTIONS OF FOULING ORDER OF SASKATCHEWAN LIGNITE ASHES

DEGREE OF FOULING	FOULING PARAMETER							SOFTENING TEMPERATURE		
	SINTERING TEST	FUSION TEST	$[Na_2O]$	$[SiO_2]$	$[SO_3]$	$[CaO]$	FOULING FACTOR	DOLOMITE RATIO	FIRST ORDER REGRESSION	SECOND ORDER REGRESSION
MOST STRONGLY FOULING	KML-3 BML BDML-1	KML-3 KML-2 UML	KML-2 BML	KML-1 BDML-1	KML-3 KML-2	KML-3 KML-1 BML	KML-2	KML-3	KML-3 KML-1 BDML-1 BML	BDML-2 KML-3
MOD-ERATELY TO STRONGLY	KML-2 BDML-2 UML KML-1	BML BDML-1 BDML-2 KML-1	BDML-1 KML-3 BDML-2 UML KML-1	PRML-1 BDML-2 UML BML PRML-2	BDML-2 PRML-2 BML	PRML-1 BDML-1 BDML-2 KML-2	KML-3 BDML-2 BML UML BDML-1	BML BDML-1 KML-2 KML-1 BDML-2 PRML-1	KML-2 UML PRML-1 BDML-2	KML-2 BML KML-1
WEAKLY TO NON-FOULING	PRML-2 PRML-1	PRML-2 PRML-1	PRML-2 PRML-1	KML-3 KML-2	UML KML-1 PRML-1 BDML-1	PRML-2 UML	KML-1 PRML-2 PRML-1	UML PRML-2	PRML-2	PRML-2 BDML-1 PRML-1 UML

Different fouling orders were obtained for the ashes derived from the Estevan coal seam, depending on whether the ash-cone fusion test or the sintering test was carried out. Since several of these coals likely have similar fouling potential, this is not unexpected. However, the ash-cone test involves experimental observations that are subjective, while interpretation of the sintering test data is not entirely obvious.

Prediction of fouling behaviour based on mineralogical data is made difficult because of the dominance of amorphous material that could either aid or inhibit fouling. Quartz is the only well-defined mineral that is present in appreciable quantities in all of the ashes. Its quantities are lowest in the non-fouling Willowbunch ashes; however, the ash that is next lowest in quartz is KML-3 which both the sintering test and the fusion test indicate to be most fouling. The quartz level is highest in KML-1 and both experimental tests indicate that, next to the Willowbunch ashes, this is the least fouling. Therefore, there appears to be no simple correlation between the quantities of prevalent minerals present and the fouling behaviour of the ash.

4.1.3. Ashes Produced at 750°C

The sintering test was also performed on ashes derived from lignites that had been ashed at the standard ASTM ashing temperature of 750°C (Figure 3).

In previous work (Smith and Szladow, 1982) an increase in compressive strength was noted as the ashing temperature was raised. This behaviour is shown again in these experiments where the magnitude of the ash compressive

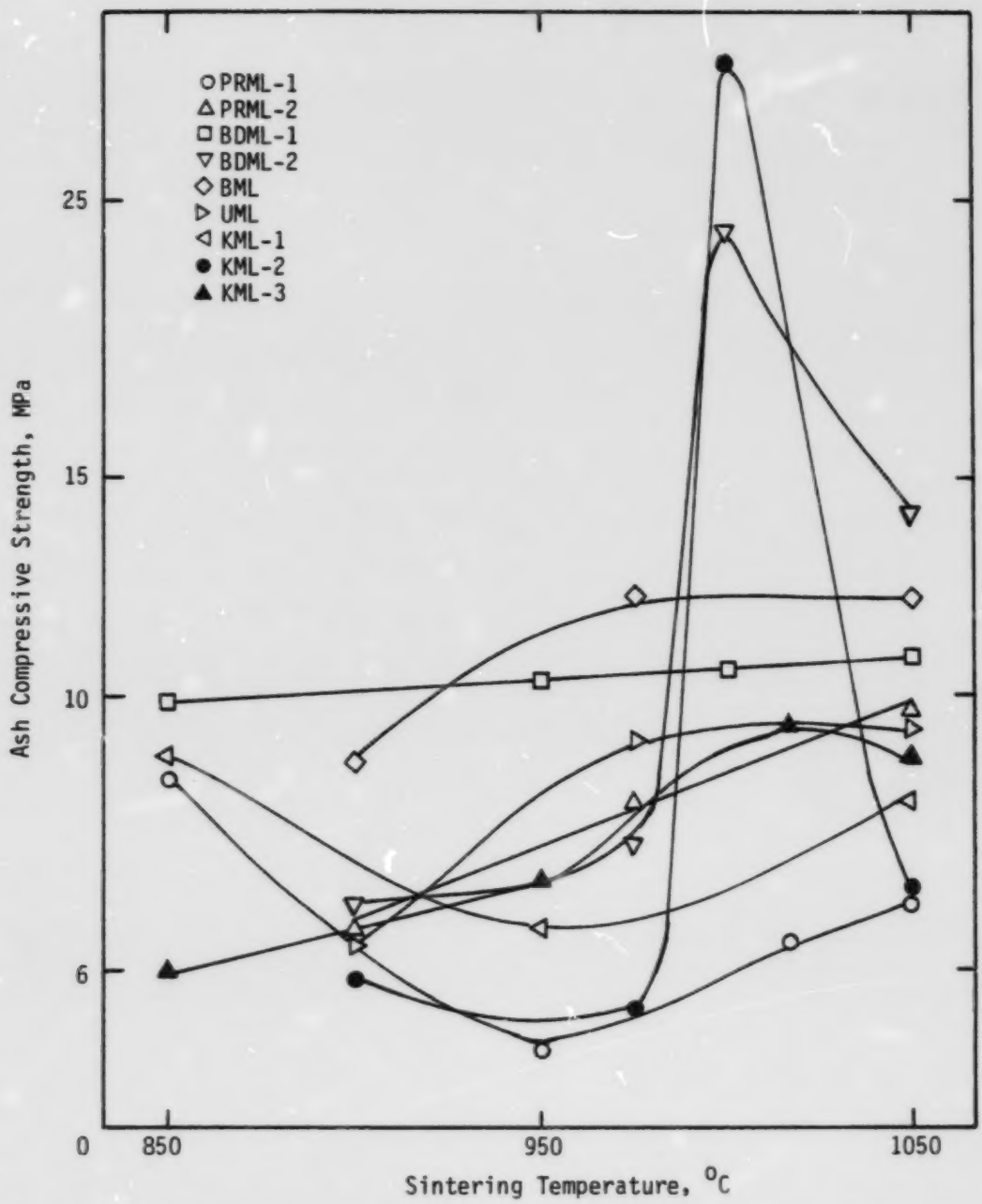


Figure 3. COMPRESSIVE STRENGTH OF SASKATCHEWAN LIGNITE ASH PREPARED AT 750°C AS A FUNCTION OF SINTERING TEMPERATURE

strength is greater than for ashes produced at 500°C.

A sintering test involving ash produced in the laboratory at 500°C has been proposed as a useful method of predicting ash fouling (Gibb, 1981). Ashing was also performed at 800°C and this procedure was said to generate reliable ash fouling predictions except in the case of Australian brown coals. Similar behaviour is noted for Saskatchewan lignite ashes since the compressive strength of PRML-2 ash has become greater than some of the ashes from the Estevan coal seam.

More pronounced peaking behaviour is noted for KML-2 and BDML-2 ashes. Based on the data on ashes produced at 750°C the following order of fouling potential is obtained:

Most strongly fouling: KML-2, BDML-2; Moderately to strongly fouling: BML, BDML-1, UML, KML-3, PRML-2; Weakly to non-fouling: KML-1, PRML-1.

These data suggest that KML-3 which was predicted to be the most fouling lignite by the previous sintering test is now comparatively non-fouling. Also KML-2 and BDML-2 which were only moderately fouling previously are now the most fouling lignites. Some of the changes in fouling order may be attributed to the loss of volatile components, such as sodium, at the higher ashing temperature. Since such a change in fouling order occurs because of this relatively minor modification, use of conditions which would produce ash similar to that generated by power plants appears desirable.

4.2. Compressive Strength of Lignite Ashes Produced by Low Temperature Plasma Ashing

Preparation of lignite ash by low temperature radio frequency plasma ashing proceeded very slowly. Lignite that had been exposed to the plasma for up to 200 h still contained up to 0.5% carbon. Over this period of time mineralogical changes had become evident by the presence of Fe_2O_3. From carbon, hydrogen and nitrogen analyses that had been performed on some ashes, elevated concentrations of nitrates became apparent after ashing periods of less than 24 h. Based on these considerations, the ashing procedure described in the experimental section was adopted.

The order of compressive strength of ash pellets obtained from plasma ashing is:

Most strongly fouling: KML-3, PRML-1, BDML-1; Moderately to strongly fouling: KML-2, KML-1, BML, UML, PRML-2; Weakly to non-fouling: BDML-2.

This differs markedly from the compressive strengths of ash pellets produced by ASTM methods. The deviation from conventionally produced ashes could be due to elevated carbon and nitrate levels present in the ashes produced by plasma ashing (Table 7). Also, there is considerable variation of the carbon and nitrate levels among the plasma-produced ashes and this would change the apparent order of ash fouling potential from what would be the case had these levels been uniform throughout the plasma ashes.

The magnitude of the compressive strengths of the plasma-produced ashes tended to be slightly higher than those of the corresponding ashes

Table 7. COMPRESSIVE STRENGTH AND CARBON, NITROGEN AND HYDROGEN ANALYSES OF SASKATCHEWAN LIGNITE ASHES PRODUCED BY LOW TEMPERATURE RADIO FREQUENCY PLASMA ASHING

1. Pressure Used to Make Pellet — 70 MPa
2. Pellet Sintering Time — 15 h
3. Pellet Diameter — 1.3 cm
4. Pellet Mass — 1.5 g
5. Sintering Temperature — 1000°C

Ash	Compressive Strength (f_c, MPa)	Carbon Content wt. %	Nitrogen Content wt. %	Hydrogen Content wt. %
PRML-1	24.7	1.51	1.17	1.01
PRML-2	11.5	1.75	0.62	0.59
BDML-1	21.2	1.41	1.23	1.05
BDML-2	5.7	2.03	0.57	0.41
BML	16.8	2.78	0.41	0.27
UML	14.1	2.53	0.46	0.38
KML-1	17.2	1.62	0.98	0.92
KML-2	19.4	2.17	0.49	0.40
KML-3	24.7	1.37	1.34	1.12

produced by ASTM methods. The compressive strength was generally greater if the ash had a relatively low carbon content; this behaviour agrees with observations of elevated compressive strengths in ASTM ashes that had their carbon content reduced (Smith and Szladow, 1982). However, the carbon contents of the plasma ashes were greater than the corresponding ASTM-produced ashes. The increased compressive strength of the plasma ashes can be explained by the smaller ash particles that resulted from the efforts to ensure that removal of organic material was maximized. This behaviour is also noted for ASTM ashes where doubling of compressive strength is observed when -325 mesh ash is tested instead of the corresponding whole ash.

5. COMPRESSIVE STRENGTH OF CCRL COMBUSTION RIG ASHES

5.1. General

Elemental analyses of the CCRL ashes reflect the additions of limestone made to the Bienfait lignite (Table 8). For lignite ashes with little or no added calcium, volatile components such as SO_3 and Na_2O are enriched in the superheater ashes compared to the slags. As the calcium content of the ashes increases, formation of $CaSO_4$ becomes more predominant and the SO_3 enrichment factor of the superheater ashes becomes less until the BF-4 ash has a higher SO_3 level in the slag than in the superheater ash. Na_2O remains enriched in the superheater fractions of the high-calcium ashes. Non-volatile components such as SiO_2 and Al_2O_3 tend to be somewhat enhanced in the slags. The slag enhancement factor is greatest for Fe_2O_3 for the Bienfait lignites that have had only small amounts of limestone added.

Ash screening showed the superheater ashes to be finer than the furnace wall ashes which in turn were finer than the slags (Table 9). However, fine particle size analysis performed on BF-0 indicated that the slags contained the smallest sized material (Figure 4).

Sintering tests performed on a given ash sample (Figure 5) indicated that at low sintering temperatures, the superheater ashes had the greatest compressive strength. As the sintering temperature was raised, the compressive strength of all the ashes tended to increase, while some of the superheater ashes passed through a maximum. Generally, the slags tended to

Table 8. COMPOSITION OF CCRL COMBUSTION RIG ASHES

COMPONENT / ASH TYPE	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O
BF-0 SLAG	34.6	19.5	24.3	0.51	0.06	10.1	2.7	1.9	3.7	0.3
BF-0 FURNACE WALL	30.3	17.2	27.9	0.51	0.08	8.9	2.2	7.6	4.3	0.3
BF-0 SUPERHEATER	25.5	17.3	14.0	0.65	0.10	16.0	3.9	10.3	7.3	0.3
BF-1 SLAG	32.0	18.4	26.8	0.53	0.09	10.0	2.3	0.5	4.3	0.3
BF-1 FURNACE WALL	25.8	15.6	22.9	0.48	0.12	13.4	3.3	9.9	5.1	0.3
BF-1 SUPERHEATER	25.4	17.0	13.0	0.52	0.07	17.7	3.7	11.5	7.3	0.2
BF-2 SLAG	34.4	18.2	21.9	0.40	0.25	15.1	2.8	0.5	3.3	0.2
BF-2 FURNACE WALL	27.2	15.1	23.7	0.41	0.20	15.0	2.7	8.3	3.8	0.3
BF-2 SUPERHEATER	26.0	16.7	12.8	0.65	0.30	22.0	3.9	7.5	5.1	0.3
BF-3 SLAG	30.9	17.7	18.0	0.46	0.25	22.4	3.5	0.7	3.8	0.2
BF-3 FURNACE WALL	23.6	13.6	19.9	0.36	0.21	20.2	2.7	11.6	4.1	0.2
BF-3 SUPERHEATER	23.2	15.5	11.0	0.62	0.29	26.2	4.0	10.6	5.6	0.2
BF-4 SLAG	18.6	9.7	7.3	0.49	0.39	46.8	2.3	11.1	1.0	0.2
BF-4 FURNACE WALL	19.6	11.2	6.9	0.50	0.38	45.1	3.5	8.7	1.3	0.1
BF-4 SUPERHEATER	20.2	13.0	7.6	0.54	0.44	43.1	4.0	5.4	2.5	0.2

Table 8. COMPOSITION OF CCRL COMBUSTION RIG ASHES (Cont'd.)

COMPONENT / ASH TYPE	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O
ONAK SLAG	59.2	11.9	12.0	0.86	0.22	10.6	2.9	0.3	1.1	1.1
ONAK FURNACE WALL	52.7	11.3	12.8	0.91	0.22	12.7	3.2	2.9	1.0	1.0
ONAK SUPERHEATER	47.6	13.2	9.6	1.08	0.30	17.2	5.2	3.2	1.1	1.1
KLIM SLAG	34.9	20.8	8.4	0.97	0.15	14.9	3.7	0.4	2.2	0.2
KLIM FURNACE WALL	43.0	19.4	10.2	0.88	0.19	13.1	3.2	4.8	2.0	0.2
KLIM SUPERHEATER	38.4	19.5	7.3	1.01	0.25	20.0	4.7	3.3	3.0	0.2

Table 9. PARTICLE SIZE DISTRIBUTION DATA FOR CCRL COMBUSTION RIG ASHES

PARTICLE SIZE		< 40 U	< 75 U	< 150 U
ASH TYPE				
BF-0	SLAG	76.9	99.9	100
BF-0	FURNACE WALL	84.9	99.9	100
BF-0	SUPERHEATER	94.2	92.0	100
BF-1	SLAG	33.8	53.7	78.3
BF-1	FURNACE WALL	63.2	84.0	99.9
BF-1	SUPERHEATER	76.7	90.2	96.6
BF-2	SLAG	65.7	99.4	100
BF-2	FURNACE WALL	81.4	99.4	100
BF-2	SUPERHEATER	91.3	99.9	100
BF-3	SLAG	31.0	43.7	69.5
BF-3	FURNACE WALL	57.5	82.2	96.7
BF-3	SUPERHEATER	83.9	95.5	98.5
BF-4	SLAG	73.3	95.6	99.6
BF-4	FURNACE WALL	84.5	98.0	99.7
BF-4	SUPERHEATER	92.2	99.0	99.8
ONAK	SLAG	87.7	99.0	99.8
ONAK	FURNACE WALL	79.0	99.8	100
ONAK	SUPERHEATER	93.2	99.9	100
KLIM	SLAG	68.2	99.0	100
KLIM	FURNACE WALL	79.0	99.5	100
KLIM	SUPERHEATER	91.6	99.7	100

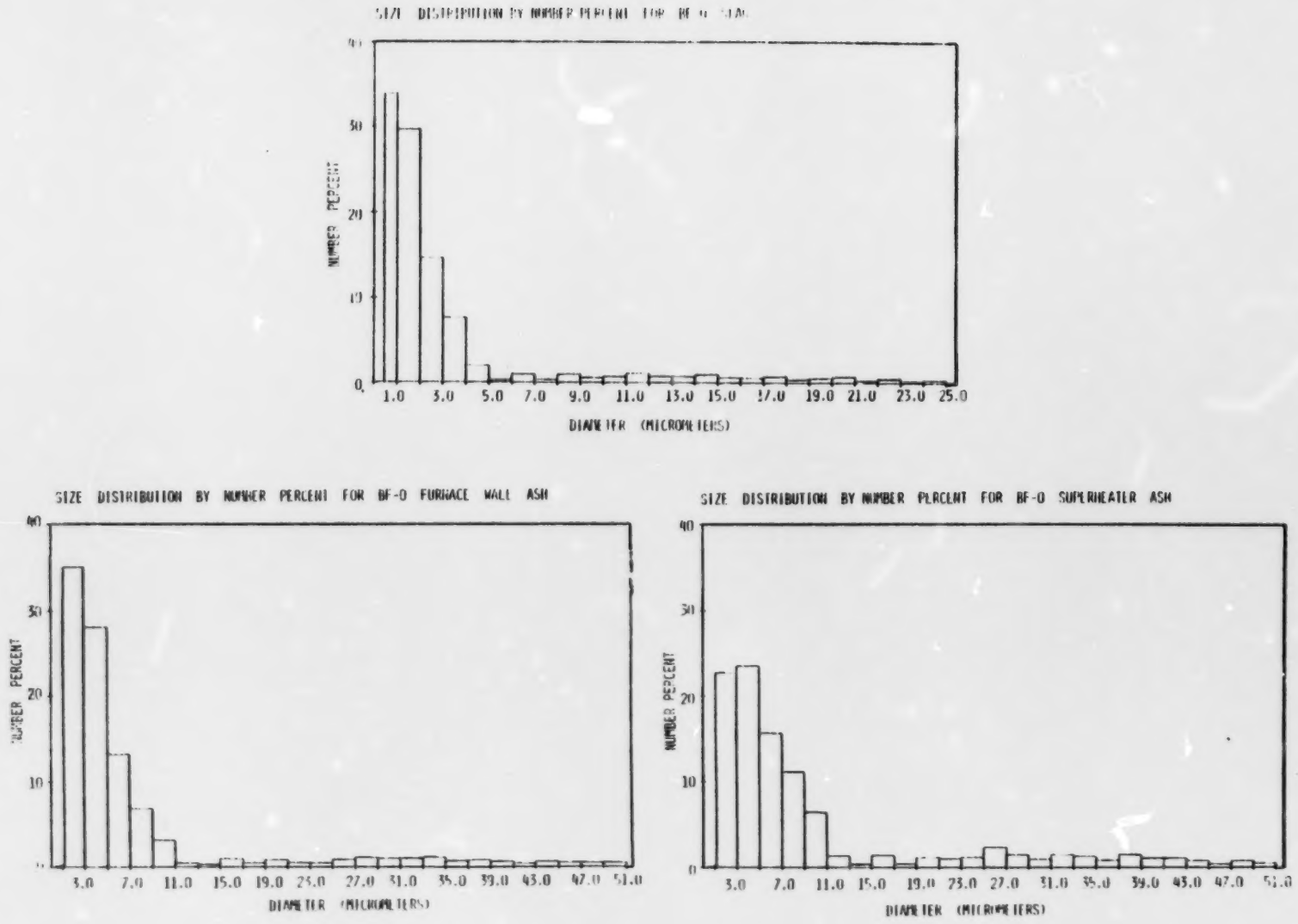

SIZE DISTRIBUTION BY NUMBER PERCENT FOR BF-O FURNACE WALL ASH
NUMBER PERCENT
DIAMETER (MICROMETERS)
SIZE DISTRIBUTION BY NUMBER PERCENT FOR BF-O SUPERHEATER ASH
NUMBER PERCENT
DIAMETER (MICROMETERS)

Figure 4. FINE PARTICLE SIZE DISTRIBUTION OF BF-O ASHES

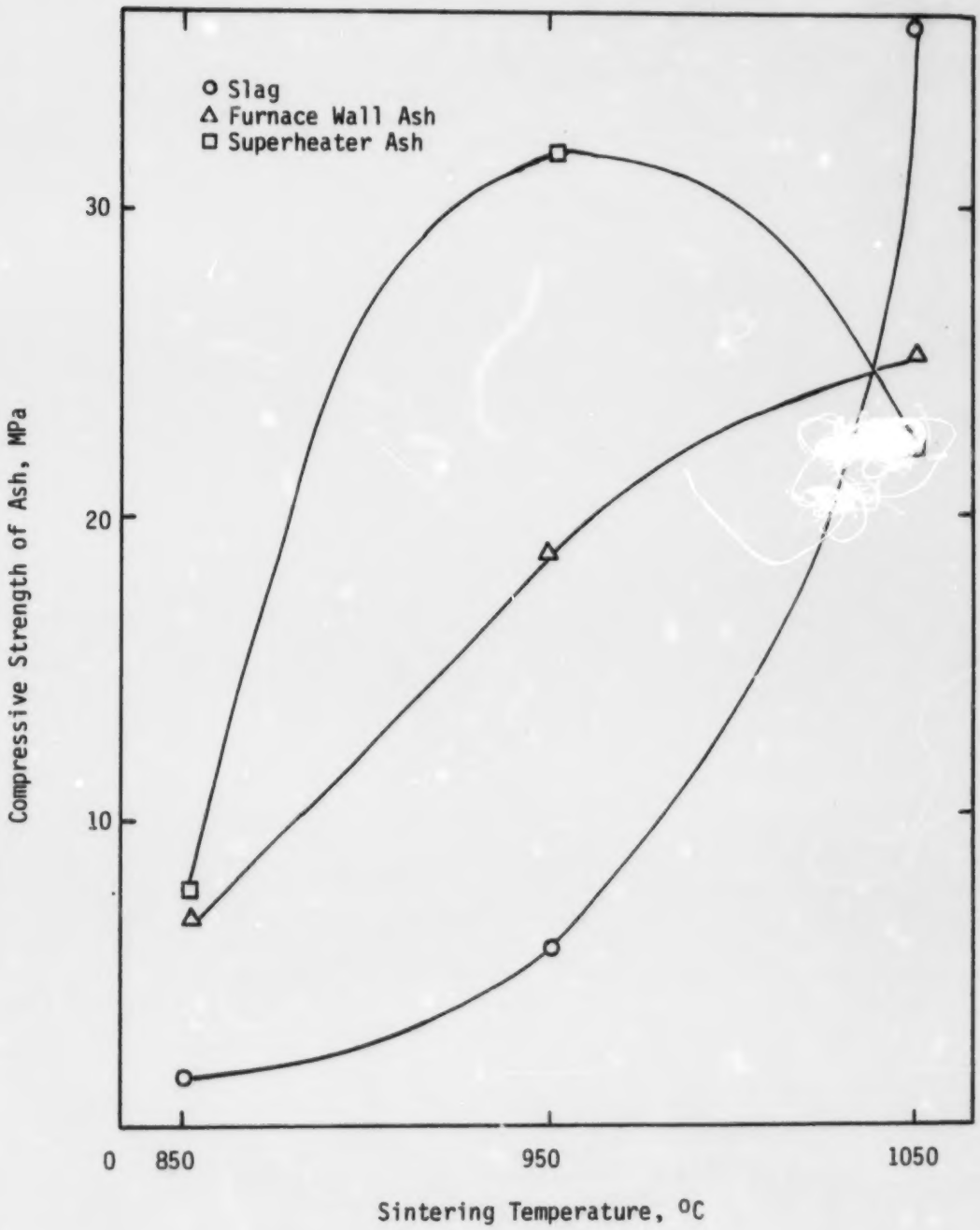


Figure 5. COMPRESSIVE STRENGTH OF BF-1 ASHES AS A FUNCTION OF SINTERING TEMPERATURE

strengthen more than the other ash fractions, and at high sintering temperatures the slags had the greatest compressive strength.

The presence of enhanced levels of volatile constituents associated with fouling and the occurrence of fewer coarse particles in the superheater ashes are consistent with their higher levels of compressive strengths after being sintered at lower temperatures. The presence of more fine particles in the BF-0 slags could account for the generally high compressive strength of slags that were sintered at higher temperatures. Also phase transitions due to mineralogical transformations at higher sintering temperature could be responsible for some of the increase in slag compressive strength.

5.2. Slags

The compressive strength *vs.* sintering temperature curves of the CCRL slags have similar characteristics (Figure 6). Compressive strengths of less than 10 MPa are observed at a sintering temperature of 850°C and initial gradual increases in compressive strength are noted as the sintering temperature is raised. Rapid increases in compressive strength occur at sintering temperature approaching 1050°C.

At lower temperatures BF-0 produced the slag with the greatest compressive strength; this is consistent with the lack of any limestone added to this lignite. At higher sintering temperatures the compressive

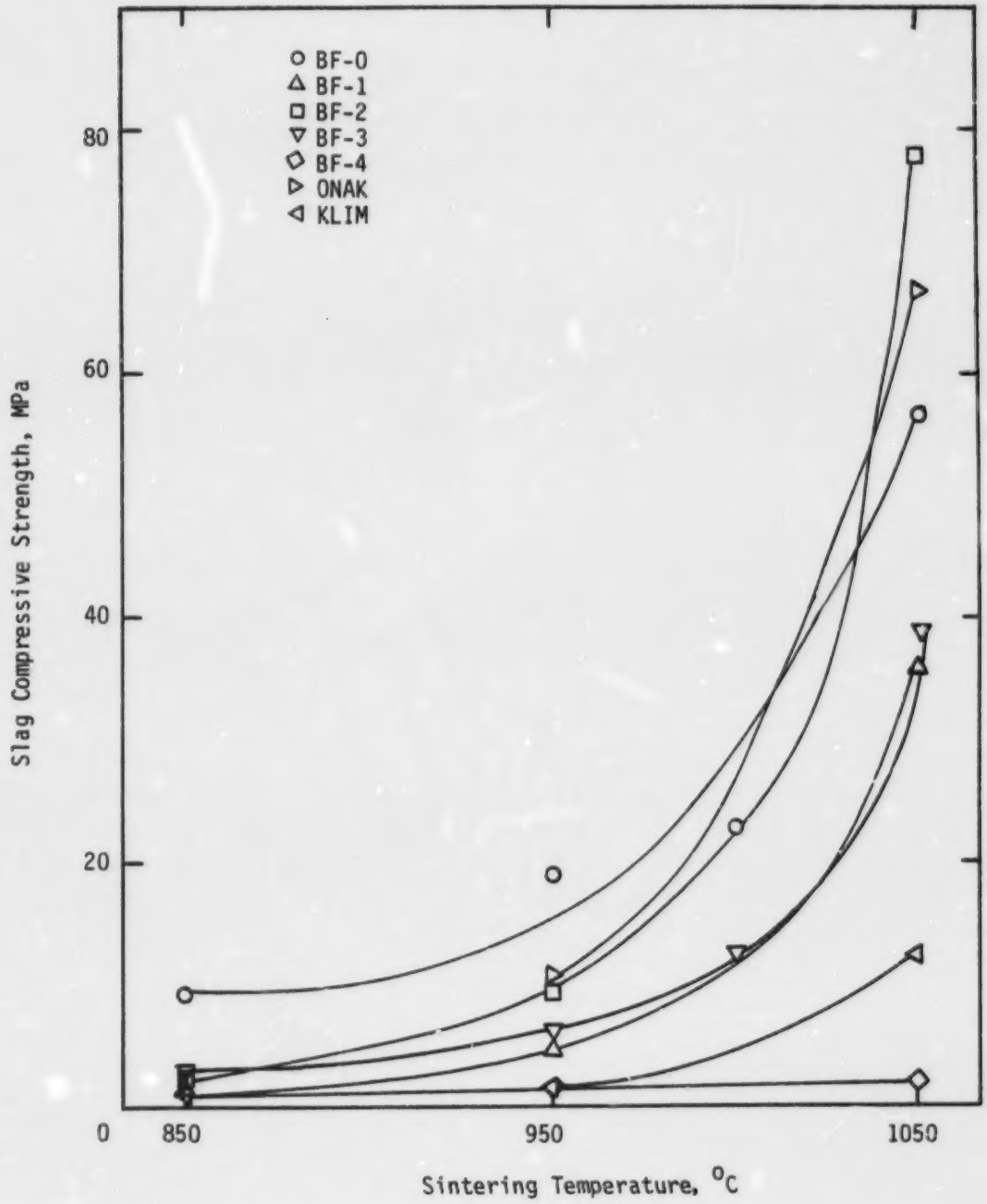


Figure 6. COMPRESSIVE STRENGTH OF CCRL SLAGS AS A FUNCTION OF SINTERING TEMPERATURE

strength of the BF-0 slag remained high but it had been exceeded by slags from BF-2 and ONAK. Although the sodium content of the ONAK slag was only 1.1%, Onakwana ashes are associated with severe fouling problems and its high compressive strength may be related to its high SiO_2 content. The high compressive strength of the BF-2 slag may be due to presence in this sample of the fewest coarse particles of all of the slags.

Since fouling is likely to be more severe at higher temperatures, the values obtained in the sintering test at the higher sintering temperature are used and the following order of slag fouling potential order is generated: Most strongly fouling: BF-0, ONAK, BF-2; Moderately to strongly fouling: BF-1, BF-3; weakly to non-fouling: KLIM, BF-4. Ash-cone fusion tests (Table 10) performed by CCRL yielded a similar fouling order except that BF-2 and ONAK slags indicated less fouling tendency than some of the other Bienfait slags.

Several sets of slag fouling potential order were generated based on elemental composition considerations discussed in Chapter 4 (Table 11). The ONAK slag is predicted to be severely fouling by empirical equations that put a high weight to silica content. In relationships where sodium content is considered important, ONAK slag does not appear to be highly fouling. The KLIM slag is generally predicted to be of low fouling potential by both of the experimental tests and empirical equations. The relationships that consider more than one constituent generally agree well with the experimental observations for the fouling order of the Bienfait slags. However, predictions based on the second order regression analysis do not correspond well with the other empirical equations or the experimental information.

TABLE 10. ASH-CONE FUSION DATA FOR CCRL COMBUSTION RIG SLAGS

ASH TYPE \ FUSION POINT	REDUCING ATMOSPHERE				OXIDIZING ATMOSPHERE			
	IDP	HP	SP	FP	IDP	HP	SP	FP
BF-0	1060°C	1095°C	1205°C	1330°C	1240°C	1270°C	1295°C	1340°C
BF-1	1070°C	1100°C	1190°C	1285°C	1250°C	1270°C	1340°C	1355°C
BF-2	1120°C	1200°C	1220°C	1255°C	1195°C	1240°C	1271°C	1350°C
BF-3	1075°C	1140°C	1145°C	1165°C	1225°C	1240°C	1245°C	1305°C
BF-4	1290°C	1315°C	1320°C	1355°C	1380°C	1405°C	1410°C	1420°C
ONAK	1125°C	1155°C	1300°C	1375°C	1125°C	1165°C	1305°C	1390°C
KLIM	1145°C	1190°C	1240°C	1310°C	1170°C	1215°C	1290°C	1321°C

Table 11. PREDICTION OF FOULING ORDER OF CCRL COMBUSTION RIG SLAGS

DEGREE OF FOULING	FOULING PARAMETER									
	SINTERING TEST	FUSION TEST	$[Na_2O]$	$[SiO_2]$	$[SO_3]$	[CaO]	FOULING FACTOR	SOFTENING TEMPERATURE DOLOMITE RATIO	SOFTENING TEMPERATURE FIRST ORDER REGRESSION	SOFTENING TEMPERATURE SECOND ORDER REGRESSION
MOST STRONGLY FOULING	BF-0 ONAK BF-2	BF-0 BF-1 BF-3		ONAK	BF-4	BF-1 BF-0 ONAK		BF-1 BF-2 BF-2	ONAK BF-0 BF-0	
MOD-ERATELY TO FOULING	BF-1 BF-3	ONAK BF-3 KLIM	BF-1 BF-3 BF-0 BF-2	KLIM BF-0 BF-2 BF-1 BF-3	BF-0	KLIM BF-2 BF-3	BF-3 BF-1 BF-0 BF-2 BF-4	ONAK KLIM BF-3	BF-2 KLIM BF-3	ONAK BF-3 KLIM
WEAKLY TO NON-FOULING	KLIM BF-4	BF-4	KLIM ONAK BF-4	BF-4	BF-3 BF-1 BF-2 KLIM ONAK	BF-4	KLIM ONAK	BF-4	BF-4	BF-4 BF-2 BF-0 BF-1

5.3. Furnace Wall Ashes

The CCRL combustion rig furnace wall ashes generally had greater compressive strengths than the corresponding slags and the increase in compressive strength with sintering temperature was more steady than in the case of the slags (Figure 7). Accelerating increases in compressive strength with sintering temperature were seen for the ONAK and KLIM ashes; a reduced rate of increase with sintering temperature was noted for BF-1 and BF-3 ashes.

From these curves a fouling potential order for the furnace wall ashes is: Most strongly fouling: BF-1, BF-0; Moderately to strongly fouling: BF-3, BF-2, KLIM, ONAK; Weakly to Non-Fouling: BF-4. Except for the presence of BF-2 and ONAK in lower positions, this order is similar to that generated for the slags. Unlike the slags studied, the BF-2 furnace wall ashes are not significantly finer than the other furnace wall ashes.

In the production of furnace wall ash, the effect of the presence of greater amounts of fouling constituents such as Na_2O and SO_3 predominates. This is reflected in the higher relative position of BF-3 over BF-2 compared to the slags, since BF-3 contains greater amounts of both components. Unlike other ashes, the ONAK furnace wall ashes are not enriched in Na_2O compared to its slag. The lack of any such increase could explain its relatively low position in the fouling order of furnace wall ashes compared to the slags.

Fouling potential orders for furnace wall ashes based on elemental

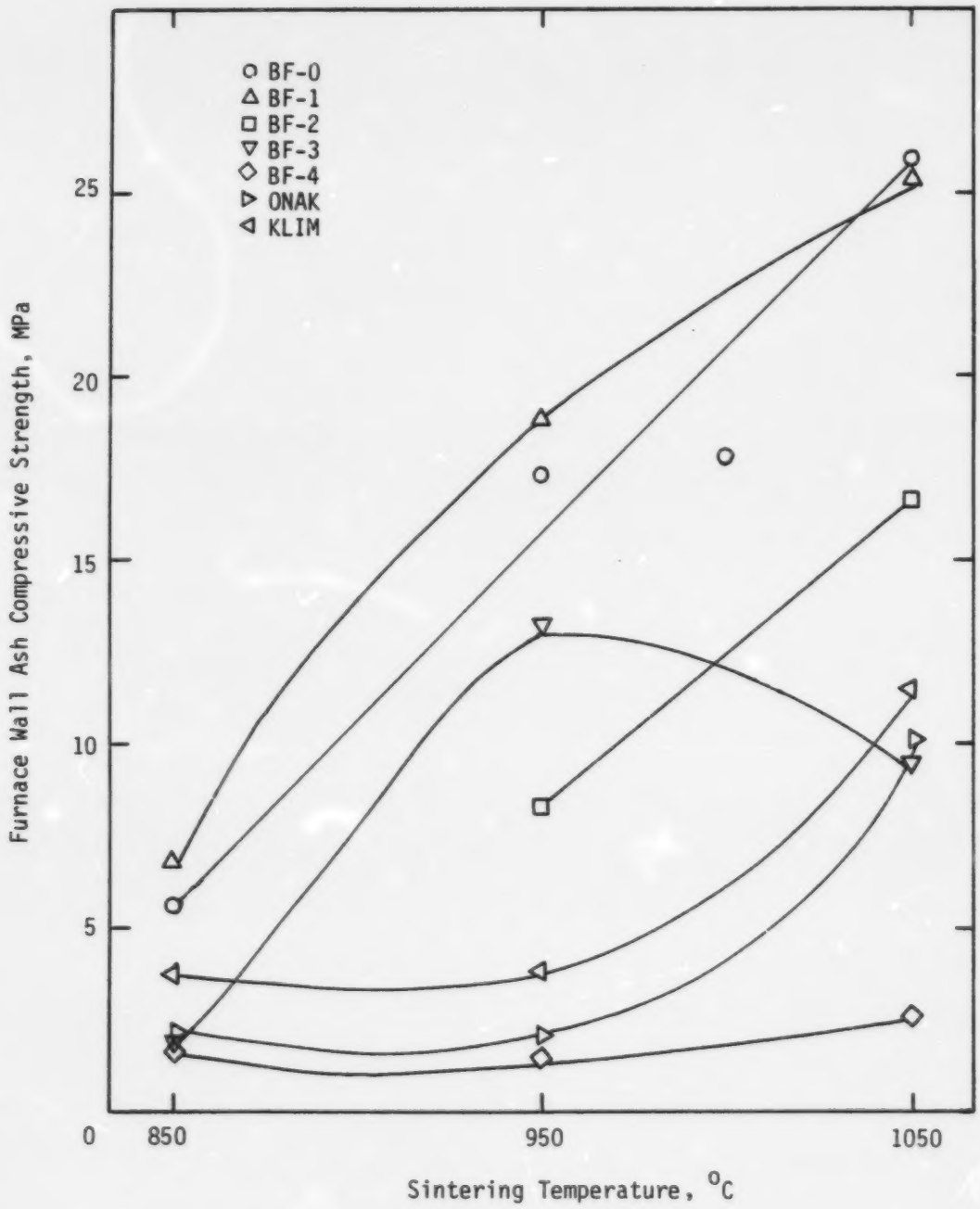


Figure 7. COMPRESSIVE STRENGTH OF CCRL FURNACE WALL ASHES AS A FUNCTION OF SINTERING TEMPERATURE

composition were similar to those generated for the slags (Table 12). Again the second order regression analysis does not correspond well with the other empirical relationships or with the experimental data. For the first order regression analysis, the order in fouling potential of the Bienfait furnace wall ashes agrees with that generated by the sintering test, but they are all in lower positions than the KLIM and ONAK ashes. This is especially anomalous because in the experimental tests, the KLIM ashes registered either the second or third lowest fouling potential.

5.4. Superheater Ashes

At lower sintering temperatures, the CCRL combustion rig superheater ashes had higher compressive strengths than other corresponding ash fractions. In contrast to the other ash fractions, initial rapid increases in compressive strength with sintering temperature were sometimes noted (Figure 8). Slower increases in compressive strength were noted for ashes that had significant amounts of limestone added. For most of the superheater ashes, the rate of increase was reduced at higher portions of the sintering temperature range studied.

The reversal of compressive strength increase with sintering temperature was most pronounced with the BF-0, BF-1 and BF-3 ashes. These superheater ashes contained over 10% SO_3, and these were the highest contents of the samples studied. This compares well with the behaviour of the laboratory ashes which exhibited compressive strength maxima when they had high SO_3 levels.

Table 12. PREDICTION OF FOULING ORDER OF CCRL COMBUSTION RIG FURNACE WALL ASHES

DEGREE OF FOULING	FOULING PARAMETER								
	SINTERING TEST	$[Na_2O]$	$[SiO_2]$	$[SO_3]$	[CaO]	FOULING FACTOR	SOFTENING TEMPERATURE DOLOMITE RATIO	FIRST ORDER REGRESSION	SECOND ORDER REGRESSION
MOST STRONGLY	BF-1 BF-0	BF-1	ONAK KLIM	BF-3	BF-0	BF-1 BF-3	BF-0 BF-1 BF-2 BF-0	KLIM ONAK BF-1	
MOD-ERATELY TO STRONGLY	BF-2 BF-2 KLIM ONAK	BF-0 BF-3 BF-2	BF-0	BF-1 BF-4 BF-2 BF-0	ONAK KLIM BF-1 BF-2 BF-3	BF-2 BF-0 BF-4	ONAK BF-3 KLIM	BF-3 KLIM	BF-3 ONAK BF-1 BF-2 KLIM
WEAKLY TO NON-FOULING	BF-4	KLIM BF-4 ONAK	BF-2 BF-1 BF-3 BF-4	KLIM ONAK	BF-4	KLIM ONAK	BF-4	BF-4	BF-0 BF-4

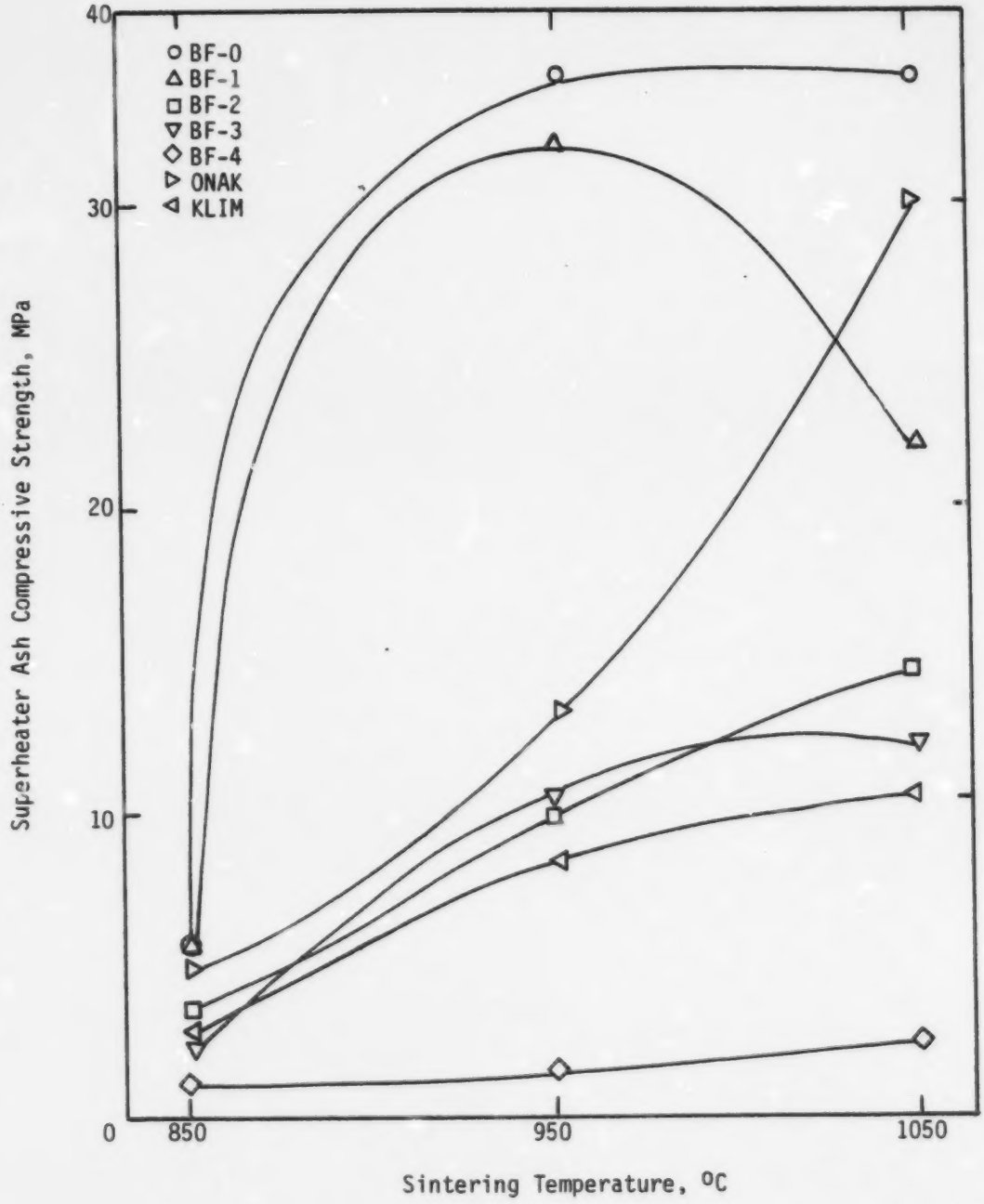


Figure 8. COMPRESSIVE STRENGTH OF CCRL SUPERHEATER ASHES AS A FUNCTION OF SINTERING TEMPERATURE

From the compressive strength curves of the superheater ashes the fouling potential order is: Most strongly fouling: BF-0, BF-1, ONAK; Moderately to strongly fouling: BF-3; BF-2, KLIM; Weakly to non-fouling: BF-4. This order is similar to that of the furnace wall ashes, but the ONAK ash is now in a higher position. The ONAK superheater ash is slightly enriched in SO_3 content while the ashes of BF-2 and BF-3 have less SO_3 than their corresponding furnace wall ashes. However, these chemical differences appear to be too small to account for ONAK superheater ashes becoming stronger than the BF-2 and BF-3 ashes. Of the superheater ashes studied, the ONAK ashes are the finest and this may account for their apparent enhanced fouling potential. Like the furnace wall ashes, the relative position of the BF-2 superheater ashes is lower in fouling order than is the case for the slags and considerations of particle size distribution and composition that occurred for the furnace wall ashes can also be applied for the superheater ashes.

Fouling potential orders for superheater ashes based on elemental composition were similar to those generated for the slags and furnace wall ashes (Table 13). Predictions from empirical equations correspond reasonably well with the observations of the sintering test. This trend even includes the second order regression analysis except for its low position of ONAK ash, but this placement also occurs from the fouling factor and dolomite ratio considerations. Again the first order regression analysis seems to place KLIM ash in an anomalously high position in fouling order.

Table 13. PREDICTION OF FOULING ORDER OF CCRL COMBUSTION RIG SUPERHEATER ASHES

DEGREE OF FOULING	FOULING PARAMETER								
	SINTERING TEST	$[Na_2O]$	$[SiO_2]$	$[SO_3]$	[CaO]	FOULING FACTOR	SOFTENING TEMPERATURE DOLOMITE RATIO	FIRST ORDER REGRESSION	SECOND ORDER REGRESSION
MOST STRONGLY FOULING	BF-0 BF-1 ONAK	BF-0 BF-1 BF-3 BF-2	ONAK	BF-1 BF-3 BF-0		BF-1 BF-0 BF-3 BF-2	BF-0 BF-1	ONAK BF-0 KLIM	
MOD-ERATELY TO STRONGLY FOULING	BF-3 BF-2 KLIM	KLIM BF-4	KLIM	BF-2 BF-4	BF-0 ONAK BF-1 KLIM BF-2 BF-3	BF-4 KLIM	BF-2 KLIM ONAK BF-3	BF-1 BF-2 BF-3	BF-1 BF-0 BF-2 BF-3 ONAK
WEAKLY TO NON-FOULING	BF-4	ONAK	BF-2 BF-0 BF-1 BF-3 BF-4	KLIM ONAK	BF-4	ONAK	BF-4	BF-4	BF-4 KLIM

6. COMPARISON OF SINTERING TEST PREDICTIONS WITH POWER PLANT EXPERIENCE

6.1. General

In the experimental program of this project, ashes produced by three different methods were examined. The techniques studied included low temperature radio frequency plasma ashing, ashing by ASTM methods and by use of the CCRL combustion rig. The ashes obtained varied in chemical and physical properties and consequently the results of the sintering tests varied with ashing techniques.

SPC has two major generating stations which produce lignite ash; the Boundary Dam Generating Station which burns lignite from the Estevan deposit and the Poplar River Generating Station which consumes Willowbunch lignite. In the former installation fouling and slagging problems regularly occur. However, during the course of this project outages due to fouling were minimal and this was attributed to different mining techniques and a mild winter in 1982-83 which placed fewer demands on the plant. In the latter installation, fouling problems do not interfere with its normal operation.

The lignite consumed at the Boundary Dam Generating Station normally produces an ash that contains 4-6% Na_2O and is moderately fouling. Lignites with up to 8% Na_2O in their ashes are sometimes burned and severe fouling problems can occur with them. In contrast, the lignites used in the Poplar River Generating Station contain less than 1% Na_2O (ash basis). In addition the fly ashes produced at the Poplar River plant are more

coarse than those produced at the Boundary Dam plant. These factors decrease the fouling potential of Poplar River fly ashes.

5.2. Ashes Produced by Low Temperature Radio Frequency Plasma Ashing

In fly ashes produced at SPC's lignite fired generating stations there is usually less than 1% hydrogen, nitrogen or carbon. The hydrogen and nitrogen contents of the plasma ashes were in the range of 0.25 to 1.5% and the carbon contents varied from 1.37 to 2.78%.

Excessive carbon content has already been related to lower compressive strength in laboratory-produced ash pellets (Smith and Szladow, 1982). This behaviour is reflected in the compressive strength of the plasma ashes. The two strongest plasma ashes are from KML-3 and PRML-1 lignites and they have the lowest carbon contents of any of the plasma ashes studied. Sintering and ash-cone fusion tests and empirical ash-composition relationships also suggest that KML-3 ashes would cause considerable fouling problems. When produced by ASTM ashing PRML-1 was the weakest of any of the ashes and it had the highest ash fusion points. Various empirical equations based on ash content also predicted that PRML-1 would produce one of the least fouling ashes. PRML-1 was taken from the Willowbunch lignite seam. Lignites from this seam are used at the Poplar River Generating Station where no fouling problems occur. Consequently, predictions on the fouling behaviour of PRML-1 are more valid when compressive strength is determined on ASTM ashes than on plasma ashes.

Plasma ashes with high carbon contents were generally low in

compressive strength. This applied to BML which other tests and relationships suggest would cause substantial fouling problems. Also, the Na_2O content of BML is sufficiently high that it would be rejected for power plant consumption.

These tests suggest that ashes produced by low-temperature plasma ashing are not suitable for predicting fouling potential by compressive strength determinations because of difficulty in achieving uniformly low levels of residual organic material. Also, the considerable length of time required to produce ash in this manner seems to preclude studies being performed on this ash on a routine basis.

6.3. Ashes Produced by ASTM Methods

Ash produced by ASTM methods retained an irregular morphology and most of the inorganic material originally in the lignite. This contrasts with power plant fly ashes which form regular spheres and drive off volatile mineral matter. SPC fly ashes regularly contains less than 1% SO_3 while the laboratory-produced ashes contained up to 20.9% SO_3. Although most of the sodium in lignite is retained in the ashes, it is concentrated on the surface of the individual ash particle. In ASTM ashes the sodium would be dispersed throughout the ash material.

The differences in chemical and physical properties of the laboratory and power plant ashes is reflected in their compressive strength behaviour. After being sintered at 1000°C, power plant ashes have compressive strengths an order of magnitude greater than corresponding ASTM ashes and

this is attributed to the surface enhancements in the power plant ashes of volatile constituents associated with fouling. Power plant ashes sintered at lower temperatures generally have insignificant compressive strengths while laboratory ashes sintered at lower temperatures may have greater compressive strengths than those sintered at higher temperatures. These characteristics are associated with the irregular nature of the laboratory-produced ashes.

When Saskatchewan lignites are ashed at 500°C, the residual carbon content is between 0.9 and 1.1% which is slightly higher than in the case of power plant ashes. When these ashes are sintered, both the lignite ashes derived from the Willowbunch coal seam have the lowest compressive strength. Ash cone fusion tests and empirical relationships also indicate these ashes to have low fouling potential and in practice these lignites cause no fouling difficulties at the power plant.

The compositions of BDML-2, UML and KML-1 suggest that they can be burned at power plants with little or no problem and this is reflected by their sintering test characteristics which suggest that only the Willowbunch lignites are less fouling. In contrast, UML is predicted to cause significant fouling by the ash-cone fusion test. It is likely that BML and KML-2 would be rejected by power plant personnel because their ash compositions are associated with severe fouling. The sintering test shows BML to be severely fouling but KML-2 only moderately fouling. The ash cone fusion test, however, predicts KML-2 to be severely fouling and BML to be moderately fouling.

Of the empirical ash composition relationships, only the ash fouling index predicts the two Willowbunch lignites to be the least fouling, while none of the relationships place both KML-2 and BML at the upper end of the ash fouling order. Therefore, the ash sintering test on lignites ashed at 500°C appears to be more useful than any of the predictions based on ash composition in determining fouling potential. The greatest chemical difference between the laboratory-produced ashes and the power plant ashes is the presence of high levels of SO_3 in the former ashes. This appears to cause the laboratory ashes to deform more readily than when SO_3 levels are low and this makes difficult interpretation of some of the compressive strength data.

When Saskatchewan lignites are ashed at 750°C, some of the sulfur is driven off but SO_3 levels of greater than 10% are still noted. The carbon content is reduced to 0.1% and this is somewhat less than what is usually noted for fly ashes. The compressive strengths of these ashes are higher than those produced at 500°C but they are still less than those of corresponding fly ashes. Also anomalously high compressive strengths due to irregular asn morphology are noted at lower sintering temperatures.

The order of ash compressive strengths is altered so that KML-2 and BML are at or near the top of the fouling potential order. However, KML-1 is now predicted to be less fouling than non-fouling PRML-2. Difficulties associated with the irregular morphologies and high SO_3 levels of laboratory ashes would have to be overcome before the ash sintering test could be used on a regular basis to confidently predict ash fouling problems associated with a given lignite.

6.4. Ashes Produced by the CCRL Combustion Rig

Microscopic examination of ashes derived from the CCRL combustion rig showed the particles to be essentially spherical in nature with the superheater ashes being of the most uniform morphology. The SO_3 contents of the slags were usually less than 1% except where large additions of limestone allowed retention of $CaSO_4$. Like fly ash, the slags generated very little compressive strength when sintered at low temperature, but rapid increases in compressive strength with sintering temperature occurred. The magnitudes of slag compressive strength were similar to those noted for power plant fly ashes. Furnace wall and superheater ashes had higher compressive strengths than the slags at lower sintering temperature, but high sintering temperature compressive strengths were less. The furnace wall and superheater ashes appear to deform more readily than fly ashes and slags. This may be due to the elevated SO_3 contents in the former ashes. Also, the CCRL superheater ashes appear to be more fine than most SPC fly ashes.

The sintering test showed a reduction in fouling potential as greater amounts of limestone were added to the parent Bienfait lignite. This is in agreement with the successful reduction of fouling problems by addition of limestone at the Boundary Dam Generating Station which burns Bienfait lignite. The Boundary Dam installation also burns lignite from the Klimax mine and fouling is noted in these coals when Na_2O content is high. The CCRL Klimax ash had a low level of Na_2O and the sintering test indicated few fouling problems associated with this ash. Ashes from Onakawana lignites are associated with considerable fouling problems. The Onakawana

ash provided by CCRL had a low level of Na_2O, but compressive strength tests of the Onakawana slags and superheater ashes indicated that fouling problems associated with this ash would be greater than expected than if just the Na_2O content of this ash was considered.

The information generated from compressive strength tests on the CCRL combustion rig ashes indicate that ashes produced in this manner can be used to predict ash fouling behaviour. However, the presence of high levels of SO_3 in some of the ashes is a source of concern; also it may be required that ashes of consistent particle size distributions are generated.

7. COMPRESSIVE STRENGTH OF LABORATORY-PRODUCED LIGNITE ASHES TREATED WITH ADDITIVES

7.1. General

SPC has successfully developed a program of adding limestone to certain lignites it burns to alleviate fouling (Anderson et al., 1977; Baker, 1981). Although limestone addition is usually very effective, difficulties are noted for a few lignites, especially if there is a high clay content. Therefore, the sintering test will be useful, not only if it can be shown to reliably predict lignite fouling, but if it can also determine additive treatment strategies which will reduce fouling.

One way of checking the value of the sintering test for establishing an additive treatment plan would be to monitor ash pellets for compressive strength as a function of additives whose effects on fouling behaviour are reasonably well understood. Additives used for fouling treatment of lignite usually contain calcium or magnesium. The presence of some impurities in a few of these additives has been attributed to enhanced rather than lowered fouling problems when such additives are used. To avoid adverse effects that may occur with some naturally occurring additives, the effects of reagent grade samples of CaO and MgO were studied. Samples of limestone that SPC used in its power plants were also tested and compared to the refined chemical additives. Dolomite which had been tested for power plant treatment was also examined.

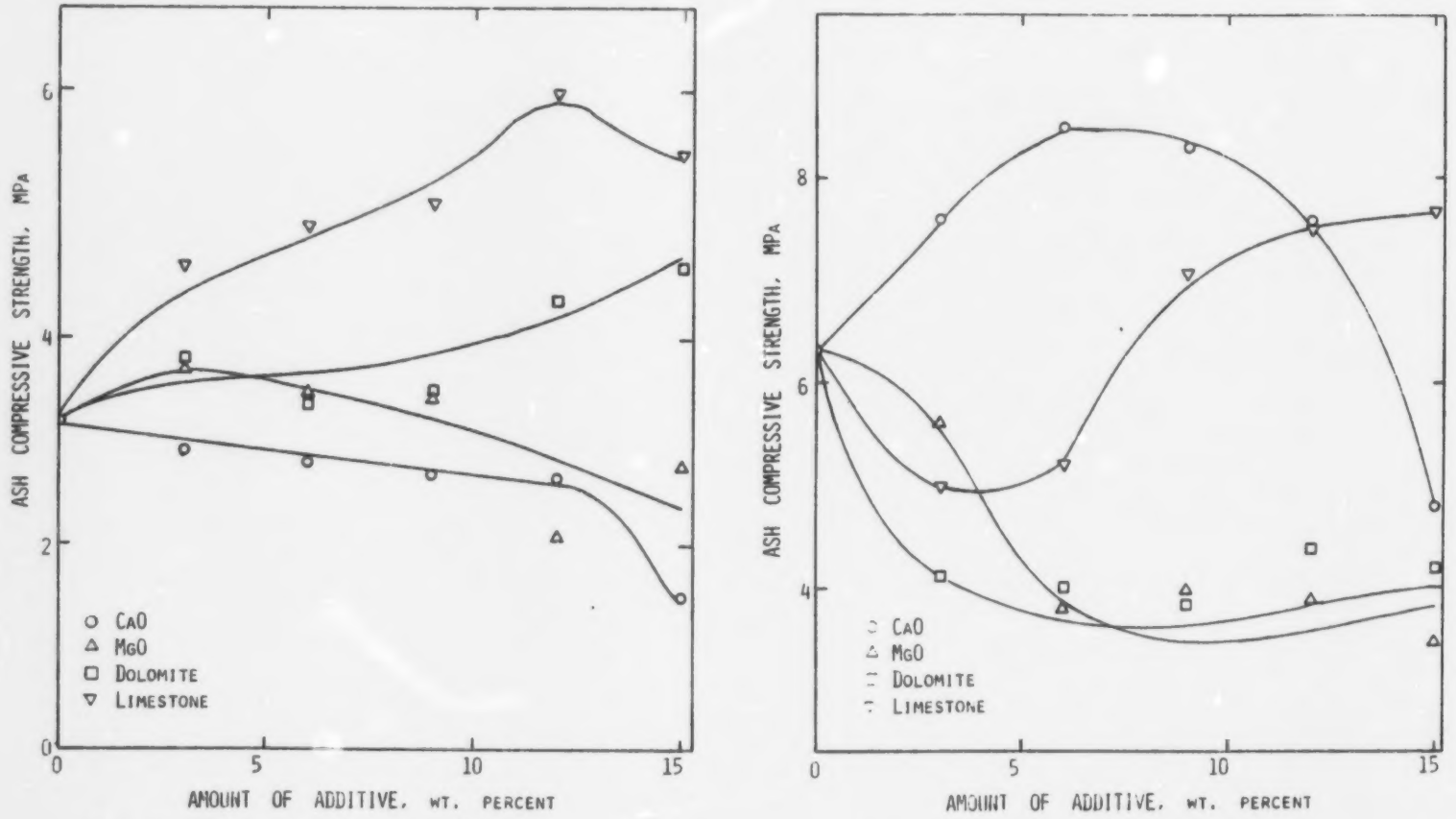
Coal ashes studied were chosen on the basis of their chemical composition and expected fouling behaviour. PRML-1 is the least fouling of

any of the lignites studied and has a very low sodium content. Therefore, the effects of additives on this lignite is of interest when compared to other more fouling lignite. BDML-1 and BDML-2 are moderately to severely fouling lignites with similar sodium contents. However, BDML-2 has a much higher SO_3 content (15.3 vs. 6.3%) with most of this difference compensated for by alumina values (10.3 vs. 21.0%). The amount of SO_3 is associated with fouling behaviour and the presence of different amounts could result in different behaviours for the various additives. KML-2 was chosen for additive study because of its sodium content (7.6%) was the highest of any of the ashes studied. In addition, the level of SO_3 in the ash was also very high (19.8%). The ash from KML-2 was also unusual because its silica concentration (23.7%) was the lowest of any of the ashes studied. Therefore, the chemical properties of this ash could lead to some interactions with the additives that would not be observed in other ashes.

7.2. Additive Tests Performed on PRML-1

The effect of the four additives on the compressive strength of PRML-1 as a function of concentration is shown in Figure 9 and the fouling tendencies based on empirical equations are listed in Table 14.

PRML-1 is a lignite not associated with fouling problems and the observed changes in the magnitude of compressive strength with additive content are not significant. Compressive strengths of pellets from ash produced at 500°C are generally less than for those produced at 750°C. Also, the degree of reduction in compressive strength of ashes produced at



(a) Ashing Temperature 500°C

(b) Ashing Temperature 750°C

Figure 9. COMPRESSIVE STRENGTH OF PRML-1 ASHES AS A FUNCTION OF ADDITIVE

Table 14. PREDICTION OF FOULING TENDENCIES OF PRRL-1 ASH TREATED WITH ADDITIVES

FOULING PARAMETER	BASE ACID RATIO	DOLOMITE RATIO	FOULING FACTOR	SOFTENING TEMPERATURE, °C DOLOMITE RATIO	FIRST ORDER REGRESSION	SECOND ORDER REGRESSION
ADDITIVE						
---	0.44	0.70	0.75	1135	1149	1229
3% CaO	0.50	0.72	0.83	1155	1168	1260
6% CaO	0.54	0.75	0.87	1170	1180	1200
9% CaO	0.60	0.77	0.94	1175	1195	1309
12% CaO	0.65	0.79	0.99	1185	1206	1330
15% CaO	0.70	0.81	1.03	1195	1219	1347
---	0.44	0.70	0.75	1135	1149	1229
3% MgO	0.50	0.72	0.83	1155	1186	1224
6% MgO	0.54	0.75	0.87	1170	1200	1221
9% MgO	0.60	0.77	0.94	1175	1224	1214
12% MgO	0.65	0.79	0.99	1185	1243	1209
15% MgO	0.70	0.81	1.03	1195	1265	1203
---	0.44	0.70	0.75	1135	1149	1229
3% Dolomite	0.47	0.71	0.78	1150	1162	1228
6% Dolomite	0.49	0.73	0.79	1160	1171	1231
9% Dolomite	0.52	0.74	0.81	1165	1180	1231
12% Dolomite	0.55	0.75	0.83	1170	1188	1253
15% Dolomite	0.57	0.76	0.84	1170	1198	1242
---	0.44	0.70	0.75	1135	1149	1229
3% Limestone	0.48	0.71	0.79	1150	1161	1237
6% Limestone	0.49	0.73	0.79	1160	1171	1231
9% Limestone	0.53	0.74	0.83	1165	1179	1259
12% Limestone	0.56	0.76	0.85	1170	1186	1270
15% Limestone	0.59	0.77	0.87	1175	1195	1279

500°C with additive is generally less than what is observed for ashes produced at 750°C. In fact, some increase in compressive strength with the mineral additives limestone and dolomite appears to occur for the ashes produced at 500°C. A net increase in compressive strength is also apparent for the ashes produced at 750°C when limestone is added.

Among the individual additives, the most notable contrast in behaviour for the ashes derived from the two different temperatures occurs for CaO. For the 500°C ash the CaO is probably the most effective additive at all concentrations studied. For the 750°C ash CaO is not an effective additive at low to intermediate concentrations with a significant increase in compressive strength taking place. At further levels of CaO, compressive strength decreases rapidly and an overall reduction in compressive strength is noted. The observation of an increase in compressive strength with additives could be due to cementitious reactions between the additive and the ash matrix (Sharlovskaya, 1970). However, when the additive is incorporated into the ash material, the overall fusibility of the ash is decreased and a reduction in compressive strength is noted.

All four empirical relationships based on ash composition indicate that a different additive would result in an ash with the greatest fouling potential. Depending on which equation is used, three of the additives are predicted to be the most effective in reducing fouling. The fouling factor predicts that the degree of fouling would be increased as the level of each additive is increased and this is because each additive increases the base-acid ratio. Softening temperature predictions based on the ash dolomite ratio or first order regression analysis indicate decreased

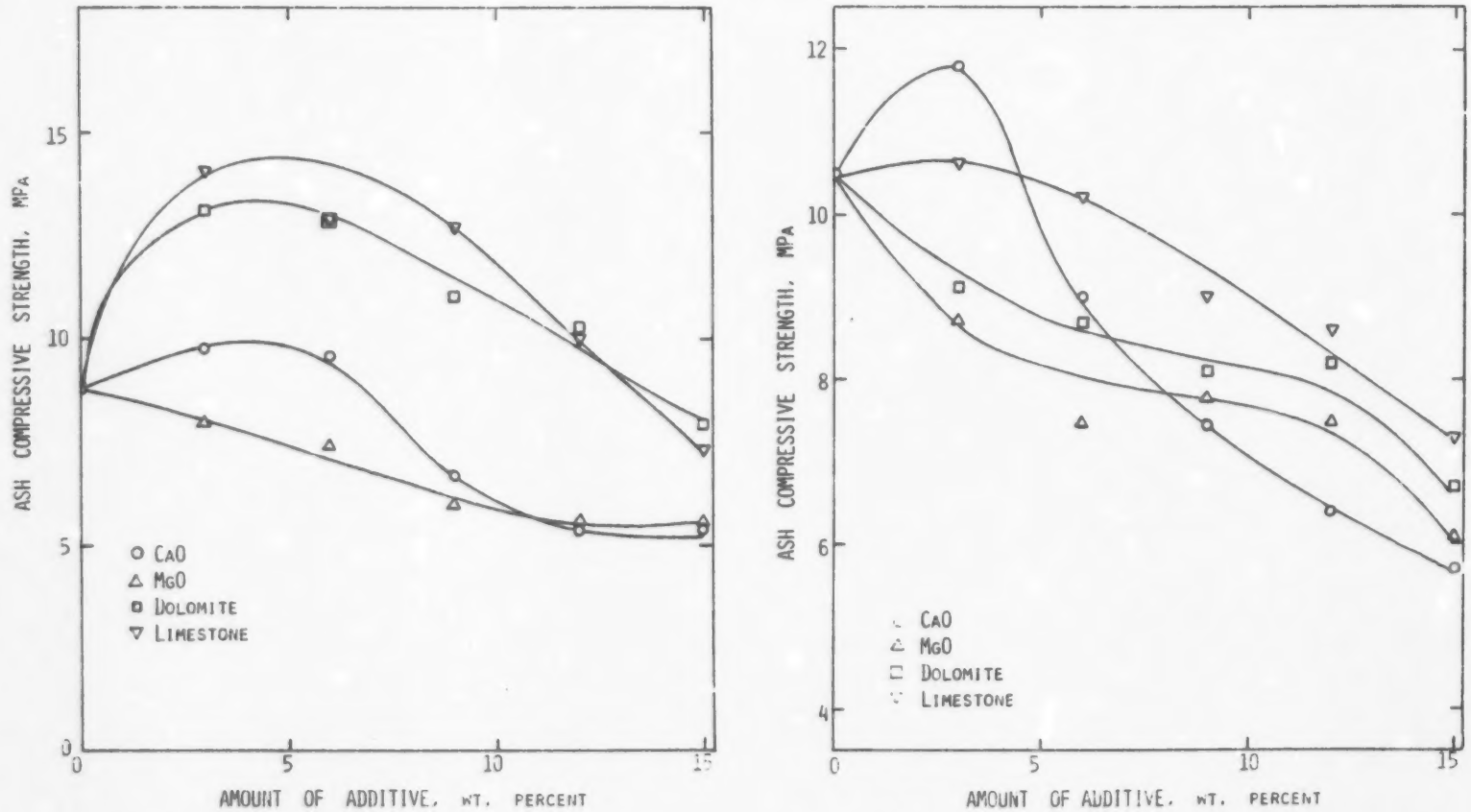
fouling with increasing concentrations of each additive. Softening temperatures derived from the second order regression analysis also generally show a decrease in fouling potential with additive level. However, the trend is reversed for MgO and increments in softening temperature do not always occur as the amount of additive is increased from one level to the next.

7.3 Additive Tests Performed on BDML-1

The effect of the four additives on the compressive strength of BDML-1 as a function of concentration is shown in Figure 10 and the fouling tendencies based on empirical equations are listed in Table 15.

BDML-1 is a lignite that is more severely fouling than PRML-1 and thus the magnitude of compressive strength occurring in these experiments is greater. There is also a more clear trend of compressive strength reductions as a function of additive level. Again, the compressive strength of the ash produced at 750°C is greater than that produced at 500°C and there is a greater degree of compressive strength reduction for the higher temperature ash. Also, for the lower temperature ash there is some increase in compressive strength associated with the dolomite and limestone.

As in the case of PRML-1, addition of CaO to BDML-1 ashes produced at 750°C initially results in a marked increase in compressive strength followed by a net reduction. However, the decrease in compressive strength occurs at lower concentrations for BDML-1 and the overall weakening is more



(a) Ashing Temperature 500°C

(b) Ashing Temperature 750°C

Figure 10. COMPRESSIVE STRENGTH OF BDML-1 ASHES AS A FUNCTION OF ADDITIVE

Table 15. PREDICTION OF FOULING TENDENCIES OF BDML-1 ASH TREATED WITH ADDITIVES

FOULING PARAMETER / ADDITIVE	BASE ACID RATIO	DOLOMITE RATIO	FOULING FACTOR	SOFTENING TEMPERATURE, °C DOLOMITE RATIO	FIRST ORDER REGRESSION	SECOND ORDER REGRESSION
---	0.45	0.62	2.97	1115	1092	1222
3% CaO	0.50	0.66	3.20	1135	1111	1257
6% CaO	0.54	0.69	3.36	1145	1132	1286
9% CaO	0.59	0.71	3.57	1150	1142	1311
12% CaO	0.63	0.73	3.71	1160	1157	1335
15% CaO	0.68	0.75	3.90	1170	1171	1354
---	0.45	0.62	2.97	1115	1092	1222
3% MgO	0.50	0.66	3.20	1135	1121	1203
6% MgO	0.54	0.69	3.36	1145	1144	1186
9% MgO	0.59	0.71	3.57	1150	1171	1165
12% MgO	0.63	0.73	3.71	1160	1194	1151
15% MgO	0.68	0.75	3.90	1170	1217	1132
---	0.45	0.62	2.97	1115	1092	1222
3% Dolomite	0.47	0.64	3.01	1125	1106	1221
6% Dolomite	0.49	0.65	3.05	1130	1115	1221
9% Dolomite	0.52	0.67	3.15	1135	1128	1218
12% Dolomite	0.54	0.69	3.18	1145	1139	1222
15% Dolomite	0.56	0.70	3.21	1150	1149	1220
---	0.45	0.62	2.97	1115	1092	1222
3% Limestone	0.47	0.64	3.01	1125	1105	1233
6% Limestone	0.50	0.66	3.11	1135	1113	1247
9% Limestone	0.53	0.68	3.21	1140	1126	1256
12% Limestone	0.55	0.69	3.24	1145	1136	1268
15% Limestone	0.58	0.71	3.33	1155	1145	1277

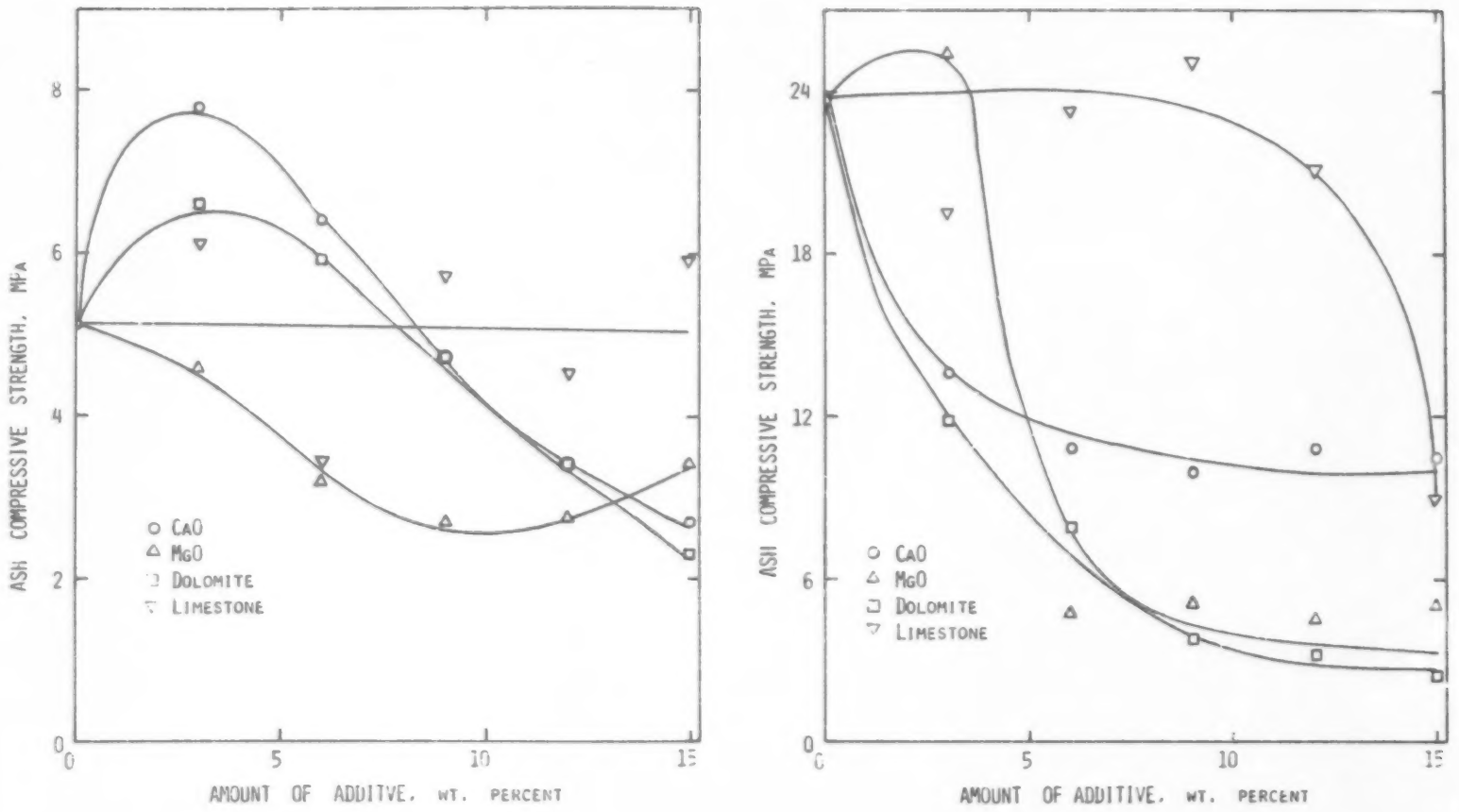
pronounced. For the BDML-1 ashes produced at different temperatures, the order of effectiveness of the four additives in reducing the fouling is similar and consistent with the order observed for PRML-1 ashes produced at 500°C.

The empirical relationships based on ash composition predict identical fouling orders compared to corresponding orders obtained for PRML-1 ashes. Again fouling factor considerations predict increasing fouling tendencies with additive levels, while predictions from the dolomite ratio and first order regression analyses indicate consistent reduction in fouling potential with additive. The second order regression analysis, in addition to predicting that additions of MgO will increase fouling behaviour, now suggests that extra dolomite will worsen any fouling problems. However, the second order regression analysis does indicate that CaO and limestone are effective anti-fouling agents.

7.4. Additive Tests Performed on BDML-2

The effect of the four additives on the compressive strength of BDML-2 as a function of concentration is shown in Figure 11 and the fouling tendencies based on empirical equations are listed in Table 16.

Like BDML-1, BDML-2 is a lignite that is more severely fouling than PRML-1 and the magnitudes of compressive strength are greater than those observed for PRML-1 ashes. BDML-2 has fairly high sulfur content and this is reflected in the considerably higher level of compressive strength that occurs for ashes produced at 750°C rather than for those produced at 500°C.



(a) Ashing Temperature 500°C

(b) Ashing Temperature 750°C

Figure 11. COMPRESSIVE STRENGTH OF BDML-2 ASHES AS A FUNCTION OF ADDITIVE

Table 16. PREDICTION OF FOULING TENDENCIES OF BDWL-2 ASH TREATED WITH ADDITIVES

FOULING PARAMETER / ADDITIVE	BASE ACID RATIO	DOLOMITE RATIO	FOULING FACTOR	SOFTENING TEMPERATURE, °C DOLOMITE RATIO	FIRST ORDER REGRESSION	SECOND ORDER REGRESSION
---	0.64	0.64	3.58	1135	1164	1044
3% CaO	0.63	0.76	3.43	1170	1143	1103
6% CaO	0.76	0.70	4.02	1155	1193	1155
9% CaO	0.83	0.73	4.26	1190	1209	1202
12% CaO	0.93	0.72	4.65	1205	1217	1234
15% CaO	0.95	0.76	4.63	1235	1232	1277
---	0.64	0.64	3.58	1135	1164	1044
3% MgO	0.63	0.76	3.43	1170	1153	1023
6% MgO	0.76	0.70	4.02	1155	1213	1034
9% MgO	0.83	0.73	4.26	1190	1239	1031
12% MgO	0.93	0.72	4.65	1205	1254	1006
15% MgO	0.95	0.76	4.63	1235	1278	1019
---	0.64	0.64	3.58	1135	1164	1044
3% Dolomite	0.60	0.74	3.26	1165	1138	1051
6% Dolomite	0.70	0.67	3.70	1150	1184	1073
9% Dolomite	0.74	0.69	3.80	1155	1196	1087
12% Dolomite	0.78	0.66	3.90	1150	1191	1089
15% Dolomite	0.79	0.71	3.85	1175	1211	1109
---	0.64	0.64	3.58	1135	1164	1044
3% Limestone	0.60	0.75	3.26	1170	1137	1069
6% Limestone	0.70	0.68	3.70	1150	1180	1091
9% Limestone	0.75	0.70	3.85	1160	1194	1130
12% Limestone	0.82	0.68	4.10	1165	1197	1148
15% Limestone	0.82	0.72	3.99	1180	1208	1178

Like BDML-1 and PRML-1, the ashes of BDML-2 produced at 500°C undergo relatively minor changes in compressive strength as the level of additive is increased, while considerable compressive strength reductions are noted for additions made to ashes produced at 750°C.

In contrast to PRML-1 and BDML-1 ashes, additions of CaO to BDML-2 ashes produced at 750°C result in no initial increase in compressive strength. However, the effectiveness of this additive at higher concentrations is not as great on either MgO or limestone. This behaviour could be related to the relatively high SO_3 level in BDML-2 ash. The ash has already generated a high compressive strength due to its high SO_3 content and addition of CaO should reduce the tendency of SO_3 to act as a fluxing agent by fixing it as $CaSO_4$. An initial addition of MgO does not reduce the compressive strength of BDML-2, suggesting MgO is not as effective as CaO in fixing SO_3. At higher levels, the addition of MgO appears to be more effective than CaO. This again could be due to the greater ability of the latter additive to fix SO_3 since SO_3 that has not combined with an additive may be volatilized and the counter-fouling tendency of that additive could be exerted without the presence of as much interfering sulfate.

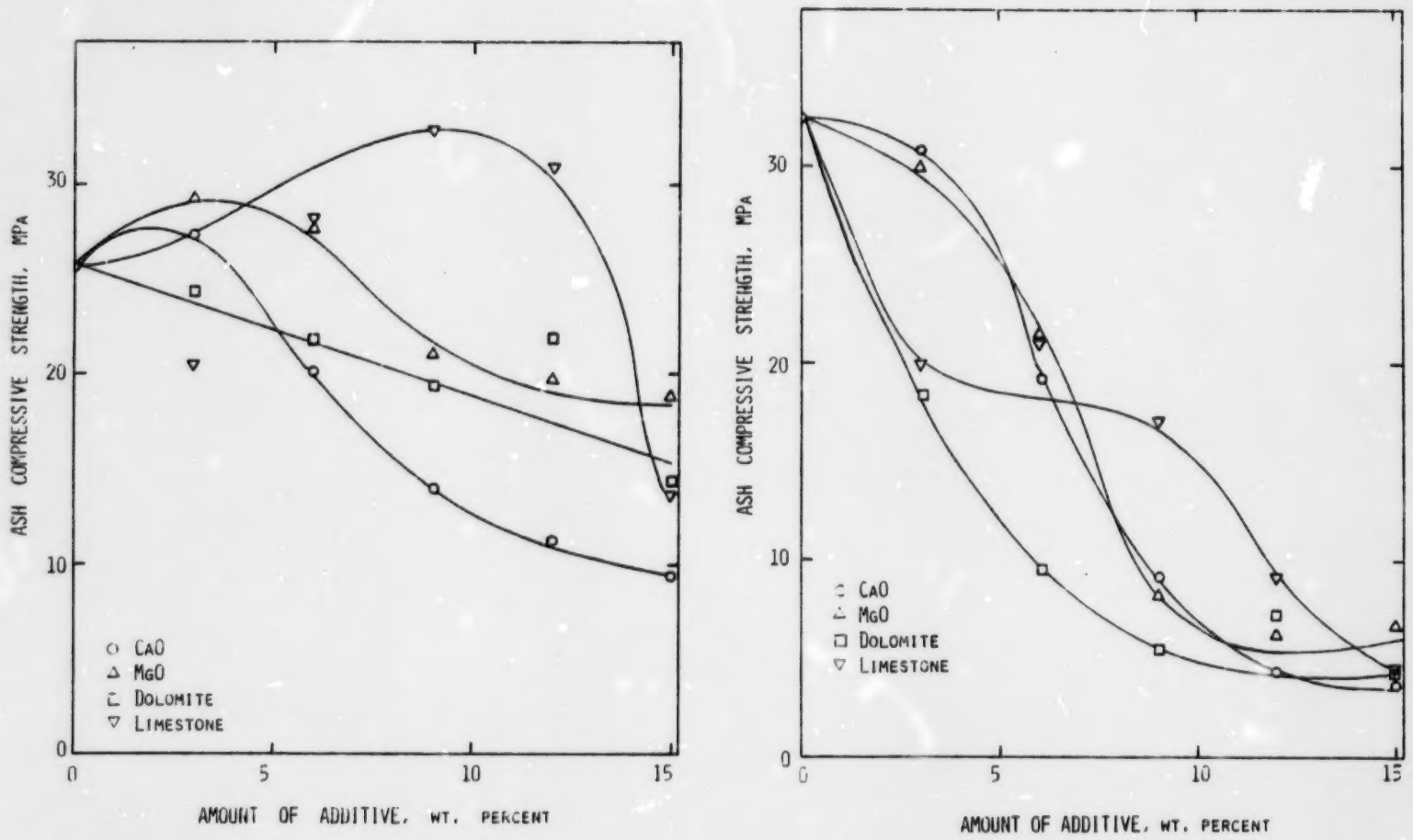
In the ash produced at 500°C, some initial increase in compressive strength with CaO addition is noted, suggesting that the presence of residual carbon interferes with the additive's tendency to fix SO_3. Addition of limestone does not appear very effective in reducing the compressive strength of this ash, perhaps because under sintering conditions used, conversion of the carbonate to sulphate is unlikely.

For the high temperature ash, dolomite appears to be the most effective additive; however, this contrasts with power plant experiences. Although the dolomite obtained for this work originated from the same deposit as that which was used in the power plant experiments, it did not have the high iron levels that were present in the dolomite used in the field trials. The studied dolomite was a good additive for all of the ashes treated. For BDML-2 ash the optimum calcium to magnesium ratios may be achieved by the addition of this material.

The empirical equations based on ash composition yield the same fouling orders that were obtained for PRML-1 and BDML-1, showing changes due to a single component are not sensitive to the different constituents already present in the ash. As for the other two ashes previously discussed, fouling factor considerations predict greater fouling with additive concentration, while the dolomite ratio and first order regression analysis indicate that fouling poential is reduced with increasing level of additive. However, the equation based on first order regression analysis suggests that an initial increase in fouling potential will occur with the mineral additives. Except for an initial increase in fouling potential for MgO, the equation based on second order regression analysis indicates a consistent reduction in fouling potential with increasing amounts of all additives.

7.5. Additive Tests Performed on KML-2

The effect of four additives on the compressive strength of KML-2 as a function of concentration is shown in Figure 12 and the fouling tendencies based on empirical equations are listed in Table 17.



(a) Ashing Temperature 500°C

(b) Ashing Temperature 750°C

Figure 12. COMPRESSIVE STRENGTH OF KML-2 ASHES AS A FUNCTION OF ADDITIVE

Table 17. PREDICTION OF FOULING TENDENCIES OF KML-2 ASH TREATED WITH ADDITIVES

FOULING PARAMETER / ADDITIVE	BASE ACID RATIO	DOLOMITE RATIO	FOULING FACTOR	SOFTENING TEMPERATURE, °C DOLOMITE RATIO	FIRST ORDER REGRESSION	SECOND ORDER REGRESSION
---	0.87	0.56	6.61	1120	1114	1123
3% CaO	0.94	0.59	6.94	1145	1131	1157
6% CaO	0.97	0.65	6.95	1175	1154	1193
9% CaO	1.09	0.65	7.60	1190	1176	1214
12% CaO	1.15	0.67	7.80	1205	1176	1237
15% CaO	1.23	0.69	8.13	1250	1191	1258
---	0.87	0.56	6.61	1120	1114	1123
3% MgO	0.94	0.60	6.94	1145	1141	1129
6% MgO	0.97	0.65	6.95	1175	1174	1145
9% MgO	1.08	0.65	7.53	1190	1191	1136
12% MgO	1.15	0.67	7.80	1205	1214	1137
15% MgO	1.22	0.69	8.06	1245	1236	1138
---	0.87	0.56	6.61	1120	1114	1123
3% Dolomite	0.91	0.58	6.71	1130	1126	1134
6% Dolomite	0.90	0.62	6.45	1150	1145	1149
9% Dolomite	0.97	0.61	6.76	1150	1148	1151
12% Dolomite	1.02	0.63	6.92	1170	1161	1168
15% Dolomite	1.04	0.64	6.87	1185	1169	1169
---	0.87	0.56	6.61	1120	1114	1123
3% Limestone	0.91	0.58	6.71	1130	1126	1142
6% Limestone	0.95	0.60	6.81	1145	1136	1157
9% Limestone	0.99	0.62	6.90	1165	1146	1174
12% Limestone	1.05	0.64	7.13	1190	1159	1197
15% Limestone	1.07	0.65	7.07	1195	1166	1211

The sintering test for ashes produced at 750°C indicated that KML-2 could be the most fouling of all of the lignites studied. Therefore, the magnitude of compressive strength in these experiments is quite high. Again the degree of reduction in compressive strength is more pronounced for ashes that are produced at 750°C rather than at 500°C. For the ashes produced at 750°C, all the additives successfully achieve a substantial and rapid reduction in compressive strength. In contrast to the results with the BDML-2 ashes, the MgO is about as effective as CaO in reducing the compressive strength of KML-2 ashes. The levels of CaO and MgO in these ashes is very similar, but the mineralogical compositions are somewhat different and these differences could be related to the relative abilities of MgO and CaO to bind SO_3 and otherwise reduce fouling behaviour. Dolomite amd limestone are also much more similar in their abilities to reduce fouling of KML-2 ashes than they are for BDML-2 ashes.

The fouling order predicted by the empirical equations is the same as observed for all of the other ashes. Again, the fouling factor indicates that fouling potential increases steadily with additive, while the dolomite ratio and first order regression analysis suggest a consistent decrease with increased concentration of additive. The second order regression analysis predicts that fouling activity is decreased with all four additives but that a minimum is achieved in the case of MgO.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1. Ashes Produced by Low Temperature Radio Frequency Plasma Ashing

The main feature of ashes produced by this technique is the extreme amount of time required to produce sufficient quantities of ash to perform tests on. Complete removal of the organic phase from these ashes requires substantial reaction time which results in elevated levels of nitrate and oxidation of iron containing minerals. Difficulties in establishing optimum ashing conditions which would minimize both the amounts of organics and the levels of nitrates resulted in ash compressive strengths that did not correspond well to their fouling behaviour.

At the present time it does not appear useful to continue tests on these ashes because of severe practical limitations.

8.2. Ashes Produced By ASTM Ashing Techniques

Ashes produced by ASTM ashing techniques from weakly or non-fouling lignites had the lowest-compressive strengths, while more severely fouling lignites generated ashes with higher compressive strengths. Some ashes, especially those with high levels of SO_3 and/or associated with severe fouling, passed through a maximum. The compressive strength of the ashes generally increased with sintering temperature. However, high compressive strengths were sometimes obtained at lower sintering temperatures. This was probably due to the irregular morphology of the ash particles and the close packing that occurred during pellet preparation.

Work aimed at achieving a better relationship between fouling tendency and the compressive strength of ashes produced by ASTM ashing techniques should include experiments where the pellets are produced at lower pressure so that the observed elevation of compressive strength at low sintering temperature is minimized. Also, tests on selected size fractions of ash particles would be useful in determining whether enhanced compressive strengths due to particle interlocking can be reduced.

Ashes produced by ASTM methods are high in SO_3 compared to power plant ashes. Ashing techniques modifications with a view to reducing the amount of SO_3 retained by the ash should be tried.

8.3. CCRL Combustion Rig Ashes

Ashes produced by the CCRL combustion rig had physical similarities to fly ashes. These ashes were low in compressive strength at low sintering temperatures and increased rapidly as sintering temperature increased. This behaviour is very similar to what is observed for power plant ashes. At low sintering temperature, superheater ashes had greater compressive strengths than corresponding slags. This is consistent with their smaller particle size and their higher levels of volatile components. At higher sintering temperature, the superheater ashes became weaker, and this could be related to high SO_3 contents which could cause pellets to deform. Lignites with greater additions of limestone yielded ashes with lower compressive strength. This corresponds well to decreases in fouling activity when limestone is used at power plants. A reasonable correlation between CCRL ash fouling potential and their compressive strengths could be

found.

Ashes produced by the CCRL combustion rig are similar to fly ashes and meaningful predictions of fouling activity and compressive strength appears possible. Also the sintering test appears useful in assessing fouling potential of different kinds of ash produced by the same lignite. However, use of the CCRL combustion rig to routinely predict fouling phenomena is clearly impractical. Therefore, effort should be expended in constructing a small-scale combustion rig that will produce spherical fly ash-like particles.

The combustion conditions of the rig should be sufficiently flexible so that different amounts of volatile material such as SO_3 can be driven from the ash so that the chemical composition of the ash is similar to what is generated at power plants.

8.4. Additive Testing

Addition of anti-fouling additives to lignites which were then ashed at 500°C resulted in relatively small reductions in ash compressive strength. The effect of the additives on lignite ashed at 750°C was more pronounced. Also, initial increases in compressive strength were frequently noted. This suggests that under the experimental conditions used, the necessary reactions between the ash and the additive did not proceed to completion.

A comparison of the effect of additives on ashes produced by ASTM

ashing and by combustion rigs would be instructive. Under combustion rig conditions, additive-ash reactions may occur more readily and relatively small amounts of additive may be required to achieve effects similar to what are noted for the ASTM ashes.

Studies of additives that increase fouling would be helpful to establish whether presently observed reductions in ash compressive strength are due to chemical phenomena and/or physical dilution effects.

8.5. Sintering Conditions

In this work a sintering time of 15 h was used. A few experiments where the sintering time was varied have indicated that compressive strength initially increases with time until a maximum is reached and then reduction in compressive strength occurs. This is attributed to a finite amount of time required for the sintering process to take place. With longer sintering times, volatile components are driven from the ash and it becomes weaker. In the power plant environment, an equilibrium between volatile component condensed and vapour phases is approached and the deposit can be strengthened with time. Also, the nature of the atmosphere surrounding the deposit may facilitate deposit material mass transfer and thus strengthen the deposit.

Tests on ash pellets sintered under varying atmospheres should be performed. Initially the atmosphere could be changed from oxidizing to reducing and the effect on compressive strength noted. From observations obtained from these experiments more detailed studies on various parameters

present in the power plant environment could be carried out.

8.6. Empirical Relationships

A variety of empirical relationships based on ash composition were applied to the ashes which had undergone the sintering test. For the Saskatchewan lignite ashes studied, of all the relationships, the fouling factor, which is not even recommended for lignites, predicted the fouling potential best. However, when the effect of adding material associated with fouling reduction was studied, the fouling factor predicted that fouling problems would get progressively worse for all of the additives studied. Also the fouling factor indicated that CCRL combustion rig ash derived from Onakawana lignite would cause less fouling problems than ash produced from a Bienfait lignite treated with a continuous 8% feed of limestone.

Predictions based on the ash dolomite ratio indicated that all of the ashes would become less fouling as increasing amounts of the tested additives were used. This is simply because the additives involved were components of dolomite. However, when SPC power plant staff tested silica as an additive because dolomite ratio considerations suggested that sufficient quantities would alleviate fouling, they found that the phenomena grew more pronounced (Anderson et al., 1977). Also, dolomite ratio considerations suggest PRML-1 to be moderately fouling when it is the least fouling of the Saskatchewan lignites studied.

First order regression analysis gave a reasonable fouling order for

the ashes studied and predicted that all of the additives tested would alleviate fouling. However, it also indicated that PRML-1 would be moderately fouling.

The second order regression analyses indicated that a non-fouling Saskatchewan lignite would be moderately fouling, predicted that a Bienfait lignite treated with additions of 1.5% limestone would yield the most fouling of the CCRL combustion rig ashes and suggested that additives containing magnesium would often enhance fouling tendencies. These calculations indicate that the usefulness of the second order regression equation studied is very limited when lignites other than those which were used to derive the relationships are investigated.

The use of empirical equations provides an approximation of relative ash fouling tendencies. However, these relationships are less reliable when ashes differ greatly in their composition. From these tests and data in the literature, it appears doubtful that equations based solely on ash composition will ever be able to predict ash fouling behaviour accurately.

Both the ash-cone fusion test and the sintering test appeared to be more useful in predicting fouling behaviour than the empirical equations. The experiments in this project indicate that much work is still required to develop the sintering test to the extent that it can be used regularly and reliably to predict ash fouling tendencies. However, development of a readily usable laboratory method that produces lignite ash that resembles power plant ash with respect to morphology and chemical composition

(especially SO_3 content) will greatly enhance the usefulness of this test. A better understanding of fouling and possible treatments will be gained if ash production can be achieved where various combustion parameters can be monitored and if additives can be readily incorporated into the ash matrix.

Table 18. COMPRESSIVE STRENGTH OF PRML-1

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)
500	850	6.0	750	850	8.6
500	850	6.4	750	850	8.6
500	850	5.8	750	850	8.6
500	850	5.3	750	850	8.6
500	950	2.5	750	950	5.2
500	950	2.4	750	950	5.3
500	950	2.5	750	950	5.0
500	950	2.8	750	950	---
500	1000	2.8	750	1000	6.6
500	1000	2.8	750	1000	5.4
500	1000	3.4	750	1000	6.8
500	1000	3.0	750	1000	6.2
500	1050	2.9	750	1050	6.9
500	1050	3.3	750	1050	6.9
500	1050	3.2	750	1050	6.9
500	1050	3.3	750	1050	6.4

Table 19. COMPRESSIVE STRENGTH OF PRML-2

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)
500	900	4.6	750	900	6.4
500	900	4.2	750	900	6.4
500	900	4.4	750	900	6.9
500	900	3.4	750	900	6.1
500	975	3.7	750	975	7.3
500	975	3.7	750	975	3.6
500	975	3.7	750	975	8.2
500	975	3.4	750	975	8.6
500	1050	3.7	750	1050	9.4
500	1050	3.2	750	1050	10.0
500	1050	3.7	750	1050	10.0
500	1050	3.6	750	1050	9.4

Table 20. COMPRESSIVE STRENGTH OF BDML-1

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)
500	850	10.1	750	850	9.5
500	850	7.9	750	850	8.6
500	850	8.3	750	850	10.7
500	850	9.8	750	850	10.7
500	950	5.8	750	950	9.9
500	950	5.9	750	950	10.6
500	950	3.9	750	950	10.2
500	950	6.5	750	950	9.9
500	1000	8.4	750	1000	10.8
500	1000	8.6	750	1000	10.4
500	1000	8.6	750	1000	10.2
500	1000	9.2	750	1000	9.9
500	1025	8.4	750	1025	---
500	1025	8.6	750	1025	---
500	1025	8.6	750	1025	---
500	1025	9.2	750	1025	---
500	1050	9.2	750	1050	9.9
500	1050	9.2	750	1050	10.7
500	1050	8.8	750	1050	10.8
500	1050	8.8	750	1050	10.4

Table 21. COMPRESSIVE STRENGTH OF BDML-2

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)
500	900	5.6	750	900	6.9
500	900	5.6	750	900	6.9
500	900	6.0	750	900	6.4
500	900	5.2	750	900	6.9
500	975	4.4	750	975	7.7
500	975	4.0	750	975	7.7
500	975	4.1	750	975	7.7
500	975	3.6	750	975	7.3
500	1000	4.7	750	1000	28.0
500	1000	5.2	750	1000	22.0
500	1000	5.3	750	1000	20.7
500	1000	5.0	750	1000	24.0
500	1050	8.6	750	1050	14.7
500	1050	8.6	750	1050	15.6
500	1050	8.6	750	1050	12.6
500	1050	7.6	750	1050	13.0

Table 22. COMPRESSIVE STRENGTH OF BML

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)
500	900	9.0	750	900	8.6
500	900	10.3	750	900	9.0
500	900	11.2	750	900	9.0
500	900	9.4	750	900	8.6
500	975	10.3	750	975	12.9
500	975	9.9	750	975	10.7
500	975	9.5	750	975	11.7
500	975	10.3	750	975	12.9
500	1050	8.6	750	1050	11.7
500	1050	8.2	750	1050	12.9
500	1050	8.6	750	1050	12.0
500	1050	9.0	750	1050	11.7

Table 23. COMPRESSIVE STRENGTH OF UML

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)
500	900	8.6	750	900	6.1
500	900	8.2	750	900	6.5
500	900	7.7	750	900	6.5
500	900	7.7	750	900	6.2
500	975	7.5	750	975	9.1
500	975	5.7	750	975	9.5
500	975	6.1	750	975	9.5
500	975	6.1	750	975	9.1
500	1050	7.3	750	1050	9.5
500	1050	8.6	750	1050	10.0
500	1050	8.2	750	1050	10.0
500	1050	9.0	750	1050	8.2

Table 24. COMPRESSIVE STRENGTH OF KML-1

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)
500	850	4.3	750	850	9.0
500	850	4.8	750	850	9.0
500	850	4.3	750	850	3.4
500	850	3.9	750	850	9.0
500	950	4.8	750	950	6.5
500	950	4.7	750	950	6.5
500	950	4.6	750	950	6.5
500	950	5.2	750	950	6.3
500	1050	7.5	750	1050	8.2
500	1050	7.8	750	1050	8.2
500	1050	7.4	750	1050	8.2
500	1050	7.4	750	1050	8.2

Table 25. COMPRESSIVE STRENGTH OF KML-2

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)
500	900	3.4	750	900	6.4
500	900	3.3	750	900	5.6
500	900	4.4	750	900	5.2
500	900	4.7	750	900	6.4
500	975	6.0	750	975	6.0
500	975	5.6	750	975	5.6
500	975	6.0	750	975	5.2
500	975	5.6	750	975	5.6
500	1000	11.2	750	1000	37.9
500	1000	9.9	750	1000	34.0
500	1000	9.9	750	1000	25.8
500	1000	10.1	750	1000	32.8
500	1050	4.1	750	1050	6.0
500	1050	3.9	750	1050	6.4
500	1050	3.6	750	1050	8.6
500	1050	4.1	750	1050	6.9

Table 26. COMPRESSIVE STRENGTH OF KHL-3

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)
500	850	12.9	750	850	6.0
500	850	14.7	750	850	6.0
500	850	12.9	750	850	6.0
500	850	13.4	750	850	6.0
500	950	4.8	750	950	7.3
500	950	4.0	750	950	6.9
500	950	4.5	750	950	7.3
500	950	4.2	750	950	6.9
500	1000	7.3	750	1000	8.7
500	1000	7.3	750	1000	10.3
500	1000	7.7	750	1000	9.4
500	1000	7.3	750	1000	9.0
500	1050	3.4	750	1050	8.7
500	1050	2.8	750	1050	8.2
500	1050	2.7	750	1050	9.4
500	1050	3.1	750	1050	9.1

Table 27. PREDICTION OF FOULING TENDENCIES OF SASKATCHEWAN LIGNITE ASHES

FOULING PARAMETER / TYPE OF ASH	BASE ACID RATIO	DOLOMITE RATIO	FOULING FACTOR	SOFTENING TEMPERATURE, °C DOLOMITE RATIO	FIRST ORDER REGRESSION	SECOND ORDER REGRESSION
PRML-1	0.44	0.70	0.75	1135	1149	1229
PRML-2	0.67	0.76	1.21	1170	1192	1200
BDML-1	0.45	0.62	2.97	1115	1092	1222
BDML-2	0.64	0.64	3.58	1135	1164	1044
BML	0.49	0.57	3.53	1105	1095	1150
UML	0.62	0.71	3.16	1155	1146	1233
KML-1	0.37	0.63	1.55	1125	1071	1151
KML-2	0.87	0.56	6.61	1120	1114	1123
KML-3	0.80	0.43	4.72	1060	1062	1081

Table 28. COMPRESSIVE STRENGTH OF CCRL ASHES DERIVED FROM BF-O

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....2.0 g

SLAG		FURNACE WALL ASH		SUPERHEATER ASH	
Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)
850	9.8	850	5.5	850	5.3
850	8.4	850	5.4	850	7.7
850	9.1	850	6.0	850	4.7
850	9.8	850	5.5	850	---
950	19.0	950	16.8	950	33.0
950	19.7	950	16.8	950	37.9
950	19.7	950	19.7	950	30.9
950	19.7	950	18.2	950	----
1000	24.9	1000	17.0	1000	----
1000	23.5	1000	17.0	1000	----
1000	19.9	1000	17.8	1000	----
1000	20.5	1000	17.8	1000	----
1050	52.6	1050	25.3	1050	35.1
1050	61.1	1050	24.6	1050	33.0
1050	59.7	1050	26.7	1050	34.4
1050	51.9	1050	27.4	1050	----

Table 29. COMPRESSIVE STRENGTH OF CCRL ASHES DERIVED FROM BF-1

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....2.0 g

SLAG		FURNACE WALL ASH		SUPERHEATER ASH	
Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)
850	1.5	850	8.5	850	6.8
850	1.5	850	6.4	850	8.9
850	1.8	850	5.4	850	---
950	6.5	950	16.8	950	30.2
950	5.2	950	20.4	950	37.2
950	6.5	950	19.0	950	28.1
1050	38.6	1050	24.6	1050	20.4
1050	35.8	1050	23.2	1050	22.5
1050	33.7	1050	28.8	1050	22.5

Table 30. COMPRESSIVE STRENGTH OF CCRL ASHES DERIVED FROM BF-2

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....2.0 g

SLAG		FURNACE WALL ASH		SUPERHEATER ASH	
Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)
850	2.0	850	---	850	4.4
850	2.2	850	---	850	3.5
850	1.8	850	---	850	2.6
950	9.8	950	7.7	950	9.1
950	9.1	950	8.7	950	11.2
950	9.1	950	8.3	950	9.8
1050	75.1	1050	19.0	1050	13.3
1050	82.1	1050	14.0	1050	16.1
1050	76.5	1050	16.8	1050	14.0

Table 31. COMPRESSIVE STRENGTH OF CCRL ASHES DERIVED FROM BF-3

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....2.0 g

SLAG		FURNACE WALL ASH		SUPERHEATER ASH	
Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (fc, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c,MPa)
850	2.8	850	2.0	850	2.4
850	3.0	850	1.9	850	2.0
850	2.6	850	2.0	850	---
850	---	850	1.9	850	---
950	7.2	950	14.0	950	14.0
950	5.7	950	12.6	950	9.1
950	5.2	950	13.3	950	8.4
950	5.4	950	----	950	----
1000	12.6	1000	----	1000	----
1000	11.9	1000	----	1000	----
1000	12.6	1000	----	1000	----
1000	12.6	1000	----	1000	----
1050	36.5	1050	11.2	1050	13.3
1050	37.2	1050	9.8	1050	11.9
1050	42.8	1050	8.4	1050	11.2
1050	----	1050	8.4	1050	----

Table 32. COMPRESSIVE STRENGTH OF CCRL ASHES DERIVED FROM BF-4

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....2.0 g

SLAG		FURNACE WALL ASH		SUPERHEATER ASH	
Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c,MPa)
850	---	850	3.3	850	1.1
850	---	850	2.6	850	1.3
850	---	850	2.8	850	---
850	---	850	2.1	850	---
950	1.3	950	1.5	950	1.8
950	1.4	950	1.5	950	1.7
950	---	950	1.5	950	1.7
950	---	950	1.4	950	---
1050	2.0	1050	3.0	1050	2.9
1050	2.2	1050	1.8	1050	2.9
1050	---	1050	2.8	1050	2.3
1050	---	1050	2.5	1050	---

Table 33. COMPRESSIVE STRENGTH OF CCRL ASHES DERIVED FROM ONAK

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....2.0 g

SLAG		FURNACE WALL ASH		SUPERHEATER ASH	
Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c,MPa)
850	---	850	1.8	850	5.1
850	---	850	2.0	850	6.4
850	---	850	2.0	850	5.2
850	---	850	---	850	5.4
950	11.9	950	2.1	950	12.6
950	9.8	950	2.4	950	14.0
950	---	950	1.8	950	14.7
950	---	950	---	950	11.9
1050	60.4	1050	9.5	1050	30.2
1050	63.2	1050	10.0	1050	34.4
1050	77.2	1050	10.0	1050	27.4
1050	----	1050	30.2	1050	30.2

Table 34. COMPRESSIVE STRENGTH OF CCRL ASHES DERIVED FROM KLIN

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....2.0 g

SLAG		FURNACE WALL ASH		SUPERHEATER ASH	
Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c,MPa)
850	1.0	850	3.8	850	2.4
850	1.0	850	3.6	850	2.9
850	1.0	850	---	850	---
950	1.3	950	4.2	950	9.8
950	1.5	950	3.5	950	7.7
950	1.4	950	---	950	7.7
1050	13.3	1050	14.0	1050	9.8
1050	13.3	1050	11.9	1050	11.9
1050	12.6	1050	----	1050	9.8
1050	11.2	1050	----	1050	---

Table 35. COMPRESSIVE STRENGTH OF CCRL ANTI-FOULING COMBUSTION ADDITIVES

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Time.....15 h
3. Pellet Diameter.....1.3 cm
4. Pellet Mass.....2.0 g

CCRL LIMESTONE		CCRL $CaCO_3$	
Sintering Temperature (T_s, °C)	Compressive Strength (f^c, MPa)	Sintering Temperature (T_s, °C)	Compressive Strength (f_c, MPa)
900	< 1	900	< 1
900	< 1	900	< 1
900	< 1	900	< 1
975	< 1	975	< 1
975	< 1	975	< 1
975	< 1	975	< 1
1050	1.9	1050	1.7
1050	1.5	1050	1.9
1050	1.7	1050	1.8
1050	1.7	1050	1.9

Table 36. PREDICTION OF FOULING TENDENCIES OF CCRL COMBUSTION RIG ASHES

FOULING PARAMETER / ASH TYPE	BASE ACID RATIO	DOLO-MITE RATIO	FOULING FACTOR	SOFTENING TEMPERATURE, °C DOLO-MITE RATIO	FIRST ORDER REGRES-SION	SECOND ORDER REGRES-SION
BF-0 SLAG	0.75	0.31	2.78	1035	1058	1366
BF-0 FURNACE WALL	0.91	0.25	3.91	1035	1098	1312
BF-0 SUPERHEATER	0.95	0.48	6.94	1085	1105	1191
BF-1 SLAG	0.85	0.28	3.66	1020	1056	1369
BF-1 FURNACE WALL	1.07	0.37	5.46	1045	1087	1234
BF-1 SUPERHEATER	0.97	0.51	7.08	1090	1117	1188
BF-2 SLAG	0.81	0.41	2.67	1045	1101	1327
BF-2 FURNACE WALL	1.06	0.39	4.03	1055	1138	1232
BF-2 SUPERHEATER	1.01	0.59	5.15	1150	1151	1241
BF-3 SLAG	0.98	0.54	3.72	1125	1155	1269
BF-3 FURNACE WALL	1.25	0.49	5.13	1115	1137	1181
BF-3 SUPERHEATER	1.19	0.64	6.66	1220	1177	1242
BF-4 SLAG	1.97	0.85	1.97	1420	1313	1303
BF-4 FURNACE WALL	1.81	0.85	2.35	1410	1317	1326
BF-4 SUPERHEATER	1.68	0.85	4.20	1400	1310	1311
ONAK SLAG	0.38	0.49	0.41	1100	1026	1227
ONAK FURNACE WALL	0.47	0.52	0.47	1100	1046	1204
ONAK SUPERHEATER	0.55	0.65	0.61	1160	1103	1275
KLIM SLAG	0.52	0.63	1.14	1125	1101	1299
KLIM FURNACE WALL	0.45	0.57	0.90	1120	1048	1272
KLIM SUPERHEATER	0.59	0.70	1.77	1150	1109	1327

Table 37. COMPRESSIVE STRENGTH OF PRML-1 WITH ADDED CaO

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	3.0	750	0	6.6
500	0	3.0	750	0	5.4
500	0	3.4	750	0	6.8
500	3 %	2.9	750	3 %	8.4
500	3 %	3.0	750	3 %	7.9
500	3 %	2.9	750	3 %	6.6
500	6 %	2.9	750	6 %	8.1
500	6 %	2.9	750	6 %	8.6
500	6 %	2.6	750	6 %	8.7
500	9 %	2.9	750	9 %	9.2
500	9 %	2.6	750	9 %	7.9
500	9 %	2.6	750	9 %	9.0
500	12 %	2.6	750	12 %	7.9
500	12 %	2.8	750	12 %	7.3
500	12 %	2.7	750	12 %	7.7
500	15 %	1.5	750	15 %	4.7
500	15 %	1.5	750	15 %	4.8
500	15 %	1.5	750	15 %	4.8

Table 38. COMPRESSIVE STRENGTH OF PRML-1 WITH ADDED MgO

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	3.0	750	0	6.6
500	0	3.0	750	0	5.4
500	0	3.4	750	0	6.8
500	3 %	3.7	750	3 %	5.3
500	3 %	3.7	750	3 %	6.8
500	3 %	3.7	750	3 %	4.8
500	6 %	3.7	750	6 %	3.9
500	6 %	3.5	750	6 %	3.9
500	6 %	3.3	750	6 %	3.7
500	9 %	3.5	750	9 %	4.6
500	9 %	3.4	750	9 %	3.9
500	9 %	3.5	750	9 %	3.7
500	12 %	1.8	750	12 %	3.7
500	12 %	2.2	750	12 %	3.9
500	12 %	2.3	750	12 %	4.0
500	15 %	3.5	750	15 %	3.4
500	15 %	2.6	750	15 %	3.5
500	15 %	2.4	750	15 %	3.5

Table 39. COMPRESSIVE STRENGTH OF PRML-1 WITH ADDED DOLOMITE

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	3.0	750	0	6.6
500	0	3.0	750	0	5.4
500	0	3.4	750	0	6.8
500	3 %	4.0	750	3 %	4.2
500	3 %	3.9	750	3 %	4.0
500	3 %	3.5	750	3 %	4.0
500	6 %	3.4	750	6 %	4.0
500	6 %	3.5	750	6 %	4.0
500	6 %	3.4	750	6 %	4.0
500	9 %	3.4	750	9 %	3.5
500	9 %	3.7	750	9 %	4.0
500	9 %	3.9	750	9 %	4.1
500	12 %	4.3	750	12 %	4.9
500	12 %	4.2	750	12 %	4.4
500	12 %	4.6	750	12 %	4.4
500	15 %	5.0	750	15 %	4.2
500	15 %	4.8	750	15 %	4.2
500	15 %	4.4	750	15 %	4.3

Table 40. COMPRESSIVE STRENGTH OF PRML-1 WITH ADDED LIMESTONE

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	3.0	750	0	6.6
500	0	3.0	750	0	5.4
500	0	3.4	750	0	6.8
500	3 %	5.4	750	3 %	5.1
500	3 %	4.0	750	3 %	5.3
500	3 %	4.6	750	3 %	4.6
500	6 %	5.1	750	6 %	5.3
500	6 %	5.1	750	6 %	5.2
500	6 %	5.2	750	6 %	---
500	9 %	5.2	750	9 %	6.4
500	9 %	5.2	750	9 %	6.4
500	9 %	5.5	750	9 %	8.4
500	12 %	6.4	750	12 %	7.3
500	12 %	6.1	750	12 %	8.4
500	12 %	5.5	750	12 %	7.0
500	15 %	5.2	750	15 %	7.7
500	15 %	5.2	750	15 %	8.4
500	15 %	5.7	750	15 %	6.8

Table 41. COMPRESSIVE STRENGTH OF BDML-1 WITH ADDED CaO

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	8.2	750	0	10.8
500	0	9.5	750	0	10.3
500	0	8.6	750	0	10.3
500	3 %	10.8	750	3 %	10.3
500	3 %	9.5	750	3 %	11.2
500	3 %	9.1	750	3 %	15.9
500	6 %	7.6	750	6 %	9.9
500	6 %	12.9	750	6 %	9.9
500	6 %	8.2	750	6 %	7.3
500	9 %	6.1	750	9 %	7.3
500	9 %	7.7	750	9 %	7.3
500	9 %	6.4	750	9 %	7.7
500	12 %	5.2	750	12 %	6.4
500	12 %	5.4	750	12 %	6.4
500	12 %	5.5	750	12 %	6.4
500	15 %	5.5	750	15 %	5.3
500	15 %	5.2	750	15 %	6.1
500	15 %	5.5	750	15 %	5.7

Table 42. COMPRESSIVE STRENGTH OF BDML-1 WITH ADDED MgO

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	8.2	750	0	10.8
500	0	9.5	750	0	10.3
500	0	8.6	750	0	10.3
500	3 %	8.2	750	3 %	8.7
500	3 %	7.7	750	3 %	8.7
500	3 %	8.2	750	3 %	8.7
500	6 %	7.7	750	6 %	6.7
500	6 %	7.7	750	6 %	8.2
500	6 %	6.9	750	6 %	7.7
500	9 %	5.9	750	9 %	7.7
500	9 %	6.3	750	9 %	7.7
500	9 %	5.9	750	9 %	8.2
500	12 %	5.5	750	12 %	7.3
500	12 %	5.7	750	12 %	8.2
500	12 %	5.7	750	12 %	6.9
500	15 %	5.5	750	15 %	6.1
500	15 %	4.8	750	15 %	6.1
500	15 %	6.3	750	15 %	6.1

Table 43. COMPRESSIVE STRENGTH OF BOML-1 WITH ADDED DOLOMITE

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	8.2	750	0	10.8
500	0	9.5	750	0	10.3
500	0	8.6	750	0	10.3
500	3 %	12.3	750	3 %	9.1
500	3 %	12.3	750	3 %	9.1
500	3 %	15.0	750	3 %	---
500	6 %	13.8	750	6 %	8.2
500	6 %	12.3	750	6 %	9.1
500	6 %	12.3	750	6 %	8.7
500	9 %	10.8	750	9 %	8.2
500	9 %	11.2	750	9 %	8.2
500	9 %	----	750	9 %	7.7
500	12 %	9.5	750	12 %	8.7
500	12 %	10.8	750	12 %	7.7
500	12 %	10.3	750	12 %	8.2
500	15 %	8.2	750	15 %	6.9
500	15 %	7.7	750	15 %	6.9
500	15 %	7.7	750	15 %	6.4

Table 44. COMPRESSIVE STRENGTH OF BDML-1 WITH ADDED LIMESTONE

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	8.2	750	0	10.8
500	0	9.5	750	0	10.3
500	0	8.6	750	0	10.3
500	3 %	14.7	750	3 %	9.9
500	3 %	12.9	750	3 %	10.3
500	3 %	14.7	750	3 %	11.7
500	6 %	12.9	750	6 %	9.1
500	6 %	12.9	750	6 %	11.2
500	6 %	----	750	6 %	10.3
500	9 %	11.7	750	9 %	9.5
500	9 %	13.8	750	9 %	9.9
500	9 %	12.5	750	9 %	7.7
500	12 %	9.9	750	12 %	8.7
500	12 %	9.9	750	12 %	7.7
500	12 %	10.3	750	12 %	9.5
500	15 %	7.3	750	15 %	7.3
500	15 %	7.3	750	15 %	7.3
500	15 %	7.3	750	15 %	7.3

Table 45. COMPRESSIVE STRENGTH OF BDML-2 WITH ADDED CaO

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sinterirg Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	4.7	750	0	28.0
500	0	5.2	750	0	22.0
500	0	5.3	750	0	20.7
500	3 %	12.1	750	3 %	13.8
500	3 %	6.7	750	3 %	14.7
500	3 %	6.7	750	3 %	12.5
500	6 %	6.5	750	6 %	13.8
500	6 %	7.7	750	6 %	9.9
500	6 %	6.1	750	6 %	9.9
500	9 %	4.7	750	9 %	10.3
500	9 %	4.9	750	9 %	9.9
500	9 %	4.5	750	9 %	9.5
500	12 %	3.0	750	12 %	10.8
500	12 %	3.6	750	12 %	11.7
500	12 %	3.5	750	12 %	10.3
500	15 %	2.8	750	15 %	10.3
500	15 %	2.5	750	15 %	9.9
500	15 %	2.7	750	15 %	11.2

Table 46. COMPRESSIVE STRENGTH OF BDML-2 WITH ADDED MgO

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	4.7	750	0	28.0
500	0	5.2	750	0	22.0
500	0	5.3	750	0	20.7
500	3 %	4.5	750	3 %	27.1
500	3 %	4.9	750	3 %	23.3
500	3 %	4.5	750	3 %	25.9
500	6 %	4.5	750	6 %	4.3
500	6 %	2.7	750	6 %	6.1
500	6 %	2.5	750	6 %	4.1
500	9 %	2.6	750	9 %	6.3
500	9 %	2.9	750	9 %	4.2
500	9 %	2.6	750	9 %	4.7
500	12 %	2.8	750	12 %	4.8
500	12 %	2.7	750	12 %	4.6
500	12 %	2.8	750	12 %	4.5
500	15 %	4.4	750	15 %	5.1
500	15 %	3.1	750	15 %	5.3
500	15 %	2.8	750	15 %	4.3

Table 47. COMPRESSIVE STRENGTH OF BDML-2 WITH ADDED DOLOMITE

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	4.7	750	0	28.0
500	0	5.2	750	0	22.0
500	0	5.3	750	0	20.7
500	3 %	7.3	750	3 %	10.8
500	3 %	6.4	750	3 %	14.6
500	3 %	6.1	750	3 %	9.9
500	6 %	6.1	750	6 %	9.1
500	6 %	6.4	750	6 %	8.2
500	6 %	5.2	750	6 %	6.4
500	9 %	4.7	750	9 %	4.3
500	9 %	4.7	750	9 %	3.3
500	9 %	4.7	750	9 %	3.8
500	12 %	3.2	750	12 %	3.3
500	12 %	3.6	750	12 %	2.9
500	12 %	3.3	750	12 %	3.2
500	15 %	2.3	750	15 %	2.8
500	15 %	2.1	750	15 %	2.5
500	15 %	2.5	750	15 %	2.5

Table 48. COMPRESSIVE STRENGTH OF BDML-2 WITH ADDED LIMESTONE

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	4.7	750	0	28.0
500	0	5.2	750	0	22.0
500	0	5.3	750	0	20.7
500	3 %	5.6	750	3 %	19.0
500	3 %	6.4	750	3 %	14.7
500	3 %	6.4	750	3 %	21.6
500	6 %	3.3	750	6 %	29.0
500	6 %	3.7	750	6 %	22.5
500	6 %	3.3	750	6 %	19.0
500	9 %	5.2	750	9 %	25.5
500	9 %	5.7	750	9 %	25.5
500	9 %	6.3	750	9 %	27.3
500	12 %	5.2	750	12 %	21.6
500	12 %	3.6	750	12 %	20.3
500	12 %	4.7	750	12 %	21.2
500	15 %	6.4	750	15 %	9.9
500	15 %	5.6	750	15 %	8.2
500	15 %	5.6	750	15 %	---

Table 49. COMPRESSIVE STRENGTH OF KML-2 WITH ADDED CaO

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, ^oC)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, ^oC)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	11.2	750	0	37.9
500	0	9.9	750	0	34.1
500	0	9.9	750	0	25.9
500	3 %	11.2	750	3 %	33.7
500	3 %	10.3	750	3 %	25.9
500	3 %	11.2	750	3 %	33.2
500	6 %	9.1	750	6 %	17.7
500	6 %	7.7	750	6 %	20.7
500	6 %	7.3	750	6 %	19.0
500	9 %	5.4	750	9 %	8.2
500	9 %	6.2	750	9 %	12.9
500	9 %	5.3	750	9 %	7.3
500	12 %	4.7	750	12 %	4.7
500	12 %	4.3	750	12 %	3.6
500	12 %	4.6	750	12 %	4.7
500	15 %	4.1	750	15 %	3.1
500	15 %	4.3	750	15 %	3.0
500	15 %	3.0	750	15 %	3.1

Table 50. COMPRESSIVE STRENGTH OF KML-2 WITH ADDED MgO

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	11.2	750	0	37.9
500	0	9.9	750	0	34.1
500	0	9.9	750	0	25.9
500	3 %	11.7	750	3 %	28.4
500	3 %	10.8	750	3 %	29.2
500	3 %	12.5	750	3 %	32.6
500	6 %	14.3	750	6 %	25.4
500	6 %	11.7	750	6 %	16.1
500	6 %	7.3	750	6 %	23.3
500	9 %	8.7	750	9 %	6.1
500	9 %	8.2	750	9 %	5.6
500	9 %	8.2	750	9 %	5.6
500	12 %	8.2	750	12 %	6.1
500	12 %	7.7	750	12 %	6.4
500	12 %	7.7	750	12 %	6.1
500	15 %	6.3	750	15 %	6.4
500	15 %	8.7	750	15 %	7.6
500	15 %	7.7	750	15 %	6.9

Table 51. COMPRESSIVE STRENGTH OF KML-2 WITH ADDED DOLOMITE

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	11.2	750	0	37.9
500	0	9.9	750	0	34.1
500	0	9.9	750	0	25.9
500	3 %	9.1	750	3 %	18.1
500	3 %	9.7	750	3 %	18.6
500	3 %	9.1	750	3 %	17.3
500	6 %	9.7	750	6 %	8.7
500	6 %	7.7	750	6 %	9.9
500	6 %	---	750	6 %	13.4
500	9 %	7.7	750	9 %	5.6
500	9 %	7.3	750	9 %	6.1
500	9 %	8.2	750	9 %	5.2
500	12 %	8.7	750	12 %	6.1
500	12 %	8.7	750	12 %	8.1
500	12 %	9.1	750	12 %	12.9
500	15 %	6.1	750	15 %	4.3
500	15 %	5.6	750	15 %	4.7
500	15 %	6.1	750	15 %	3.6

Table 52. COMPRESSIVE STRENGTH OF KML-2 WITH ADDED LIMESTONE

1. Pressure Used to Make Pellet.....70 MPa
2. Pellet Sintering Temperature.....1000 C
3. Pellet Sintering Time.....15 h
4. Pellet Diameter.....1.3 cm
5. Pellet Mass.....1.5g

Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)	Ashing Temperature (T_a, °C)	Amount of Additive (wt pct)	Compressive Strength (f_c, MPa)
500	0	11.2	750	0	37.9
500	0	9.9	750	0	34.1
500	0	9.9	750	0	25.9
500	3 %	9.1	750	3 %	21.2
500	3 %	7.7	750	3 %	19.5
500	3 %	7.7	750	3 %	18.9
500	6 %	10.3	750	6 %	21.2
500	6 %	10.8	750	6 %	21.2
500	6 %	12.5	750	6 %	20.3
500	9 %	13.8	750	9 %	16.0
500	9 %	9.9	750	9 %	16.0
500	9 %	16.0	750	9 %	19.5
500	12 %	12.1	750	12 %	9.1
500	12 %	12.9	750	12 %	9.1
500	12 %	12.1	750	12 %	9.1
500	15 %	6.1	750	15 %	4.7
500	15 %	4.9	750	15 %	4.3
500	15 %	---	750	15 %	4.7

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